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A THEORY OF EVOLUTION OF LAGOON DEPOSITS ON SHORELINES OF EMERGENCE[1]

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ABSTRACT

The tidal delta at Barnegat Inlet and deposits at other New Jersey inlets shown on coast charts suggest an orderly evolution of deposits in tidal lagoons on young shorelines of emergence.

In an effort to deduce this evolution from the factors governing tidal inlets, hypotheses are presented according to the following sets of assumed conditions : (1) the inlets open simultaneously and remain stationary; (2) the inlets open successively and remain stationary; (3) the inlets open simultaneously and migrate rapidly; and (4) the inlets open successively and migrate rapidly. Each hypothesis is presented in a series of five stages of development of the same part of the same shoreline, but it is believed that the different stages all may exist on different parts of the same shoreline at the same time.

The theory is tested by comparison of the idealized stages of development with coast charts of New Jersey and Long Island. Both shores exhibit features corresponding to the deductions, New Jersey features indicating nearly stationary inlets, whereas Long Island inlets indicate rapid migration away from the headland. The success of the test of the theory on these two shores seems to indicate that tidal inlets on young shorelines of emergence may produce a definite evolution of lagoon deposits. It is believed that such lagoon features may be useful in the interpretation of shoreline history, and especially of inlet behavior.

INTRODUCTION

A survey of the vicinity of Barnegat Inlet, New Jersey,[2] showed that the large, tidal delta in Barnegat Bay landward of the inlet

[1] Presented before the Seminar in Geomorphology at Columbia University.

[2] "A Study of Barnegat Inlet, New Jersey, and Related Shoreline Phenomena" was the writer's doctorate dissertation presented to the Dept. Geol., Princeton University, in 1933. The report is published in Shore & Beach, Vol. II, No. 2.

(Fig. 5) was composed of beach-drifted débris and deposited by flood tidal currents. Chart studies of other New Jersey inlets reveal striking similarities between the patterns of marshes and channels, suggesting that deposition in the lagoon may follow definite laws and proceed through an orderly evolution. The principles thought by Johnson[3] to control the behavior of tidal inlets are reviewed briefly in an effort to deduce working hypotheses for the evolution of lagoon deposits. If the deposits at all tidal inlets are the products of flood tidal currents, as at Barnegat Inlet, their evolution should bear a close relationship to the factors governing tidal inlets.

FACTORS CONTROLLING TIDAL INLETS

The following postulates, with slight modifications, are taken from Johnson's *Shore Processes*:[4]

1. "With the same tidal range along two offshore bars, if the longshore current is weaker on one than on the other, the bar with the weaker current will have more and wider inlets."

2. "As sedimentation and marsh growth decrease the water volume in a lagoon so will the longshore currents increase their effect, finally becoming able to narrow, or even to close some of the inlets."

3. "An inlet, once closed, may never reopen, although a new inlet may be cut by storm wave attack."

4. "Tidal action tends to maintain, but not to produce inlets."

To summarize, may be added:

5. "Waves cut inlets, tidal currents preserve them and longshore currents close them."

Corollaries include:

6. "Lagoons tend to be broad and bars continuous near the headland."

7. "Lagoons tend to be narrow and broken by many inlets far from the headland."

8. "If the bar be almost continuous, little offshore sediment can reach the lagoon and that little is largely deposited by tidal currents."

9. "The end of a lagoon near the headland is least apt to have a constant salinity. Conversely, where numerous inlets keep the lagoon salty, marine grasses thrive and tend to fill the lagoon."

[3] Douglas Johnson, *Shore Processes and Shoreline Development* (New York: John Wiley & Sons, 1919), pp. 365–82.

[4] *Ibid.*, pp. 366–68.

If, as noted on preceding pages, waves tend to produce inlets, tidal currents to maintain them, and longshore currents to close them, then the life of an inlet is controlled by the ratio between tidal and longshore currents. The sediment carried by these currents, in turn, is a function of the distance from the headland. Therefore, if sediment of fluvial or eolian origin be excepted, lagoon deposits are an expression of the relation between tidal currents, longshore currents, and the distance from the inlet to the headland. This may serve as a guiding principle in formulating a theory of lagoon deposition. Actually, eolian and fluvial material is present in tidal lagoons, but as long as such sediment constitutes a small fraction of lagoon deposits, the preceding guiding principle may be found to hold true.

HYPOTHESES OF LAGOON DEPOSITION

A theoretical consideration of natural processes should, as far as possible, include all the factors affecting such processes. In the attempt to deduce the evolution of lagoon deposits, the numerous factors are arbitrarily considered under four hypotheses. These hypotheses attempt to construct the evolution of lagoon deposits according to four sets of assumed conditions.

1. The inlets open simultaneously and remain stationary.
2. The inlets open successively and remain stationary.
3. The inlets open simultaneously and migrate rapidly (away from the headland).
4. The inlets open successively and migrate rapidly (away from the headland).

Certain factors which might complicate the shoreline history and which are, therefore, temporarily omitted from the hypotheses, are taken into consideration in the succeeding pages when the deduced evolutionary stages are compared with actual shorelines. For example: (*a*) the effect of fluvial or eolian detritus is temporarily omitted; (*b*) the tidal range is assumed to be uniform along the deduced shorelines; (*c*) all the inlets are assumed to have equal cross sections; and (*d*) marsh growth is considered to be dependent upon salinity in accordance with the preceding postulate No. 9.

Because of the omission, although only temporary, of any natural processes from the deduced evolution, the theoretical stages of lagoon

deposition cannot be expected precisely to duplicate conditions in nature. The disparity between the deduced and actual conditions may indicate the importance of factors which operate in nature but not in the hypothetical lagoon evolution.

PROCEDURE FOLLOWED IN CONSTRUCTION OF THE IDEALIZED DRAWINGS

The four hypotheses are represented diagrammatically in Figures 1, 2, 3, and 4. Each figure is a series of five stages in the depositional history of the same portion of a tidal lagoon, with the earliest stage at the left, and the final stage at the right, of each figure. The mainland is at the left and the ocean at the right in each case. The headland, from which longshore sediment is transported, is north, i.e., above each diagram.

The lagoon is wider near the headland, where more abundant débris prevents rapid retrogression of the shoreline, than it is farther from the headland (lower part of the diagrams). While marsh deposits are filling the lagoon, the barrier beach normally is migrating landward; therefore, the lagoon is slightly narrower in each succeeding stage, from left to right. Although only a few inlets are shown on the diagrams, they are spaced closer together far from the headland, according to postulate No. 7. The marsh, therefore, grows more rapidly in the lower part of each drawing.

It is true that débris from the headland will probably be deposited most rapidly near the headland, producing the largest tidal deltas in that part of the lagoon. But this process necessarily lessens the quantity of sediment carried far from the headland, so that the bar far from the headland receives less protective material to offset the ravages of storm-wave attacks. As Johnson[5] has shown, waves then attack the bar with greater effect, causing it to migrate shoreward and opening numerous inlets which are more likely to remain open if the supply of longshore débris is slight. The many inlets produce a more constant salinity in the lagoon, which fosters rapid marsh growth. The marine grasses undoubtedly aid in the deposition of fine sand, silt, and clay to produce deposits more extensive than those near the headland, where the great tidal deltas are built. The Barnegat Inlet tidal delta contains a very small percentage of silt

[5] *Ibid.*, p. 369.

and almost no clay or organic matter. The lagoon sediments near Cape May, on the other hand, are soft oozes of clay, silt, and organic material, with a small percentage of sand.

The apparent paradox which results in most rapid lagoon-filling far from the headland when the largest deltas are found in the other part of the lagoon is due, therefore, to this great difference in character of lagoon sediments and to the fact that the lagoon is much narrower and more easily filled by a small amount of sediment than near the headland where lagoons are widest and broken by few inlets.

HYPOTHESIS I

THE INLETS OPEN SIMULTANEOUSLY AND REMAIN STATIONARY

Five stages of filling of the lagoon on the same shoreline are shown in Figure 1. The *first stage* is dominated by the tidal deltas. The beginnings of marsh at inlet *C*-1 are due to the more constant salinity far from the headland. The marshy islands occur on the delta, because this is the first part of the lagoon deposit to reach high-water level.

The *second stage*, *A*-2, *B*-2, and *C*-2, is dominated by marsh islands upon the deltas. Marsh has also bordered the lagoon and grown out upon the shoal water near the shores. Much of the flood tidal current still flows through the distributary channels at *A*-2 and B-2, but at *C*-2 the growth of marsh has attached the delta to the mainland. The "tied delta" phenomenon is best developed in the *third stage*, when all the tidal deltas impinge against the mainland and are joined to it by salt marshes. Each marsh mass opposite an inlet divides the lagoon into bays roughly equidistant from the inlet. It is proposed that such bays be called "delta bays," and the third stage may then be called the "early delta bay" stage in lagoon deposition. As soon as the deltas become attached to the mainland, forming "delta bays," the flood tidal current no longer radiates from the inlet but is split into two main channels by the marsh mass on the delta. Deposition then proceeds along, rather than across, the lagoon.

The *fourth*, or "late delta bay," stage is shown at *A*-4, *B*-4, and *C*-4. Increased deposition and marsh growth have produced a stage in which salt marsh is more prominent than open water. The delta bays are still present, but reduced in size and connected to the inlets

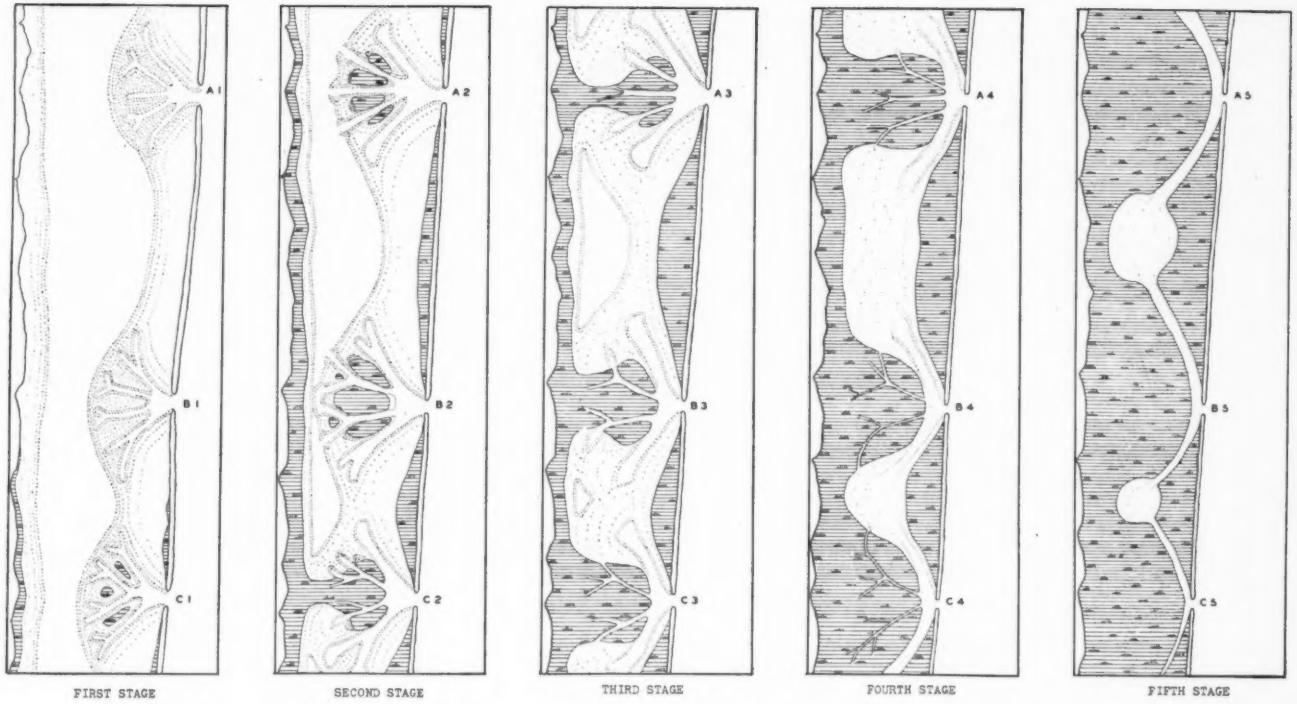


FIG. 1.—Idealized stages of deposition in a tidal lagoon if the inlets open simultaneously and remain stationary

by more narrow channels, owing to the gradual landward migration of the offshore bar. The delta channels are also very narrow, but their deltaic origin is still unmistakable. In the last, or *fifth, stage* the lagoon is completely filled, with the exception of roughly circular bays equidistant from the two inlets which drain them. Because tidal movements are largely vertical with very little current action at this stage, such bays have been named "slack-water bays"; and the "slack-water bay" stage is the last event before the lagoon becomes entirely marsh-filled.

The reader is reminded that the features shown in Figures 1, 2, 3, and 4 are idealized. It is recognized that inlets in nature do not all have the same size, nor do they remain absolutely stationary; also that salt-marsh channels may meander with infinite irregularity. No attempt is made to represent such irregularities in the diagrams, because the gross features then would be less apparent. In the comparison which is made in the following pages between the idealized drawings and actual coast charts, the diagrams must not be studied with attention to minute details. They represent only the major features of the lagoon, much generalized. It is notable, however, that the circularity of the slack-water bays in the fifth stage of Figure 1 does not greatly exceed that of Great Sound or Jarvis Sound in Figure 8.

HYPOTHESIS 2

THE INLETS OPEN SUCCESSIVELY AND REMAIN STATIONARY

A shoreline in five stages of development with the same processes at work as in Figure 1, but not in the same order, is shown in Figure 2. First only inlet *A* is present, then *B* breaks through the bar, and finally a third inlet, *C*, begins the depositional processes outlined under Hypothesis 1. The general patterns of the lagoon deposits under the two hypotheses are quite similar, the differences being in the arrangement of the features.

Because it is older than *B* or *C*, inlet *A* progresses to the early delta-bay stage first, even though it is nearest the headland. When inlet *C* is cut through the barrier beach, however, the increased deposition and more constant salinity causes rapid deposition in that portion of the lagoon. The ultimate effect of succession of inlets should be the asymmetrical location of the slack-water bays with respect to the inlets (as at *C*-3, Fig. 2).

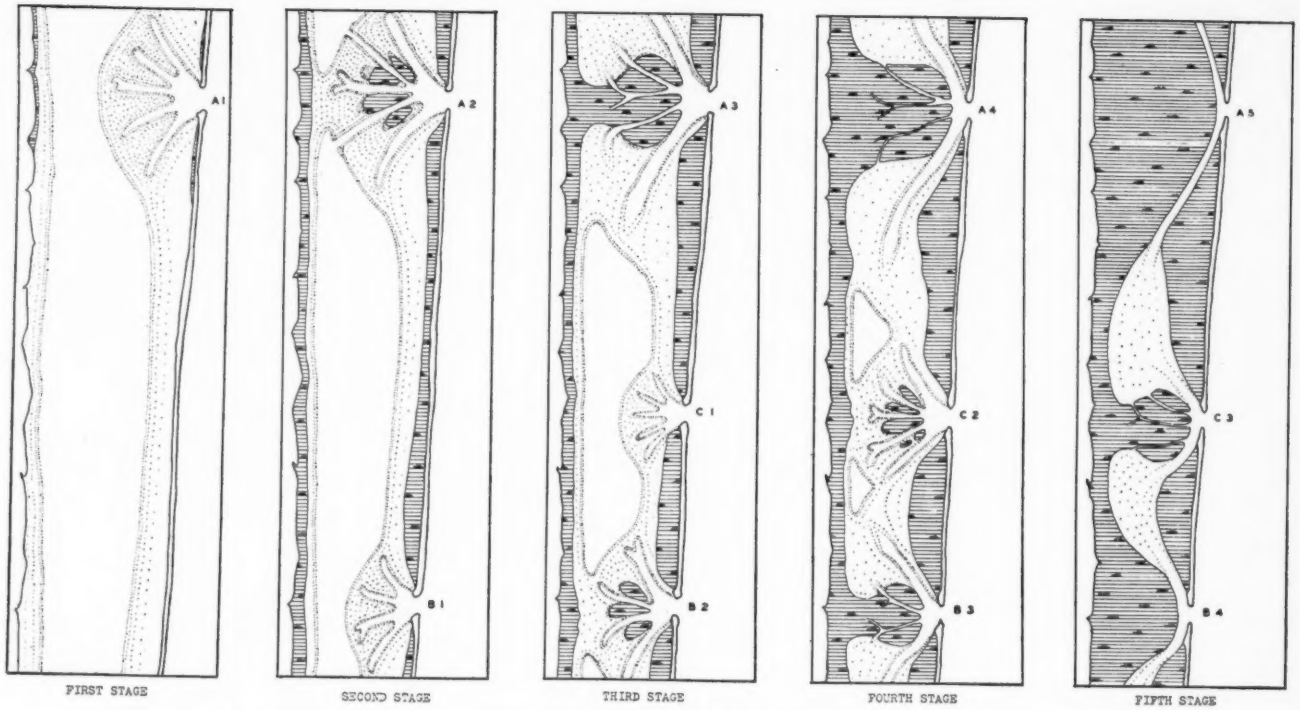


FIG. 2.—Idealized stages of deposition in a tidal lagoon if the inlets open successively and remain stationary

The conditions shown at *A*-4, *C*-2, and *B*-3 probably would be duplicated by inlets of equal age if *C*-2 were very small, *B*-3 a little larger, and inlet *A*-4 larger than either of them. The importance of stationary inlets is evidenced by the symmetry of delta marshes and delta bays. Notice that Figure 2, unlike Figure 1, does not show most rapid marsh-filling at the lower end of the lagoon. This reversal of the conditions postulated is due to the younger age of inlet *C*, which locally offsets the normal effect of closer spacing of inlets.

HYPOTHESIS 3
THE INLETS OPEN SIMULTANEOUSLY AND MIGRATE RAPIDLY SOUTHWARD (AWAY FROM THE HEADLAND)

Five stages of lagoon deposition under the assumed conditions are shown in Figure 3. The *first stage* (*A*-1, etc.) shows slightly asymmetrical tidal deltas, and the inlets are south of their respective deltas, owing to the southward migration. Marsh begins at the lagoon shores, because the deltas are not deposited rapidly in one place, but spread across and along the lagoon as a thickening wedge of sediment. The delta asymmetry is best shown in the *second stage*, when marsh begins to grow upon the deltas. As the inlets migrate along the shore, they cut new distributary channels. Landward migration of the bar narrows, and finally closes off, the earlier delta channels. The closing-off of old, and the opening of new, channels is one of the dominant features of rapid inlet migration when the lagoon is still relatively free of marsh growth.

The *third stage* (*A*-3 and *B*-3) finds the delta sediments nearly covering the lagoon. The continued inlet migration causes most rapid marsh growth adjacent to the barrier beach and at the headland end of each delta. That is, marsh is widest on the *A*-3 delta at its upper end; marsh on the *B*-3 delta is nearer to the new position of *A*-3 than *B*-3, etc. In the *fourth stage* marsh dominates the lagoon, and bays are retained in the old delta channels across the lagoon. The *fifth*, and last, stage shows a rudely rectangular pattern of marsh channels, with the only remaining open water restricted to narrow arms of the sea parallel and adjacent to the headland side of the offshore bar at each inlet. The keynote of lagoon deposition if the inlets migrate rapidly is, therefore, asymmetry and irregularity, as contrasted with the symmetrical patterns produced by stationary inlets.

The rate of inlet migration represented in Figures 3 and 4 may be considered excessive by some students of the problem. The fact that inlets do, or do not migrate at precisely this speed is of little importance. Pictures have been drawn (Figs. 1 and 2) of stationary inlets, even though inlets may not remain stationary in nature. The two extremes of no migration and rapid migration may lie outside the limits of true inlet behavior and have been drawn deliberately to represent extreme cases. If any of the idealized drawings approach conditions in nature, they should provide a useful indication of past history. In any event, present-day inlets should produce lagoon deposits either similar to the deduced extreme conditions or intermediate between the two. If chart studies show that this is the case, the idealized drawings shall have served their purpose.

The inlets on both Figures 3 and 4 have been drawn to conform to Gulliver's rule,[6] showing appropriate offsets and overlaps due to the rapid, southward migration. It is believed that the depositional features described would not vary widely if the longshore drift were strong enough to cause rapid inlet migration, whether it be continuous or intermittent. In this connection, Patton[7] thinks of inlet migrations as "repeated shiftings within fixed limits rather than as a migration indefinitely in one direction." Whatever the true habits of tidal inlets may be, the deduced hypotheses of lagoon history may serve to enlarge our store of knowledge of shore processes.

HYPOTHESIS 4
THE INLETS OPEN SUCCESSIVELY AND MIGRATE RAPIDLY SOUTHWARD

No great differences exist between the conditions in Figure 4 and the preceding one. The same rate of inlet migration is represented and the lagoon filled similarly, but with differences in the arrangement of channels and bays. Notice that in Figure 3 the lagoon becomes uniformly shallow in the fourth stage but that in Figure 4 the open bay between inlets *A*-4 and *B*-3 is large and still deep at the landward edge of the lagoon. The effect of succession of inlets is, therefore, the presence of unfilled portions of the lagoon often farther from the headland than more completely filled parts of the lagoon.

[6] F. P. Gulliver, "Shoreline Topography," *Proc. Amer. Acad. Arts & Sciences*, Vol. XXXIV (1899), p. 179.

[7] R. S. Patton, personal communication to the author, March, 1933.

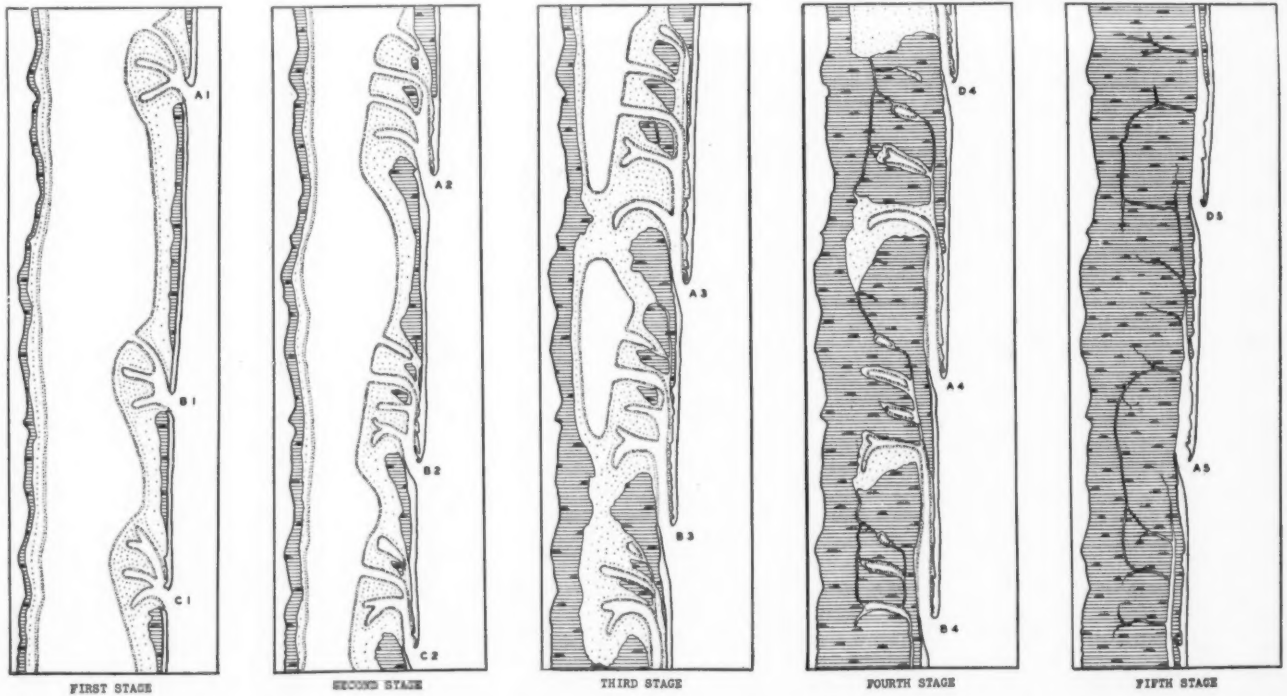


FIG. 3.—Idealized stages of deposition in a tidal lagoon if the inlets open simultaneously and migrate rapidly southward

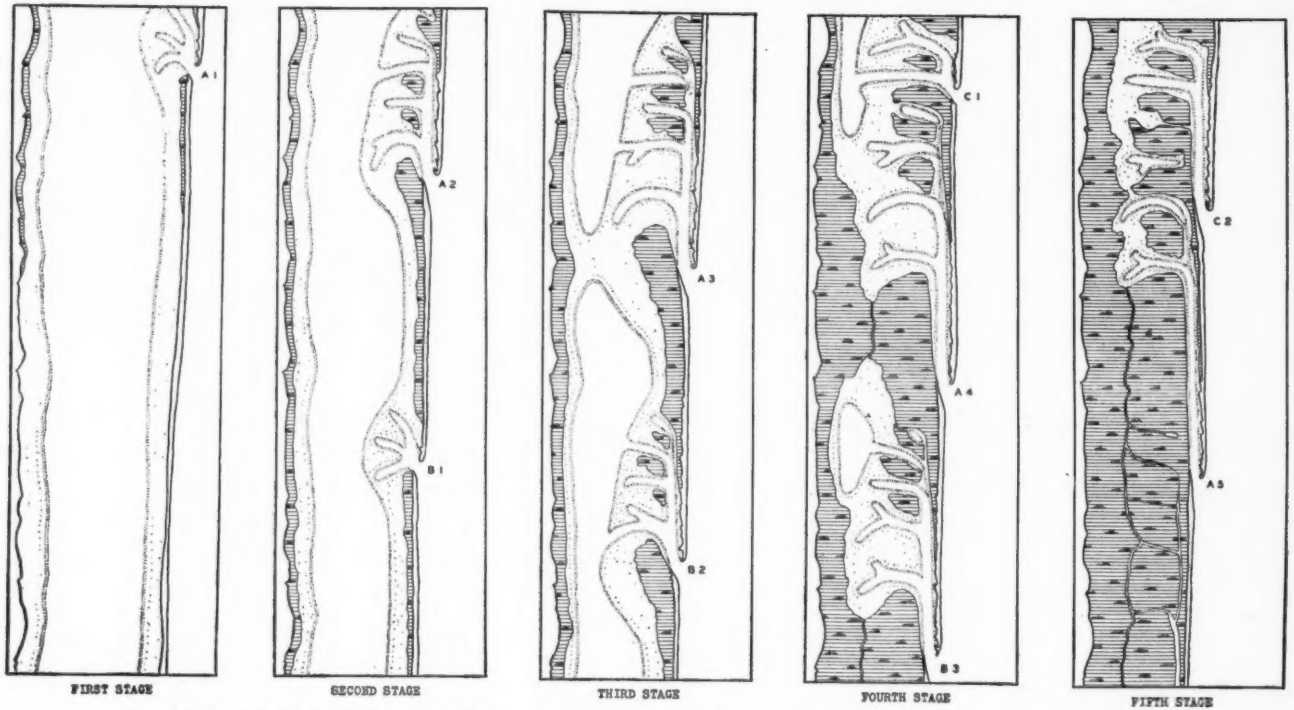


FIG. 4.—Idealized stages of deposition in a tidal lagoon if the inlets open successively and migrate rapidly southward

The fourth stage in Figure 4 also might have been produced by inlets of the same age if *C*-1 were small, *B*-3 larger than *C*-1, and *A*-4 larger than either of them.

SPACE AND TIME RELATIONS BETWEEN THE DEDUCED STAGES OF DEPOSITION IN TIDAL LAGOONS

Most of the foregoing description of the suggested depositional history of tidal lagoons has been concerned with the time, or age, relations on a particular section of shoreline. It has been deduced that a portion of a lagoon may be filled progressively according to the idealized drawings. Only a few inlets are shown on these drawings, but it is evident that a shoreline of emergence may have a very long barrier beach, or offshore bar, broken by numerous inlets.

If the length of a lagoon is great, all the idealized stages of evolution may exist along the same coast at the same time, but, of course, in different parts of the long lagoon. In accordance with the inlet postulates, the hypothetical lagoon is narrower, and inlets are more closely spaced, far from the headland. If the lagoon is long enough, that portion farthest from the headland should be narrowest and become filled most readily. Therefore, the initial, or delta, stage of deposition should be nearest the headland and the last stage at the other end of such a long lagoon. It is not necessary for all stages of development to be represented in one lagoon; but if the last, or slack-water bay, stage is present, then examples of progressively earlier stages should occur as one approaches the headland. Thus, the slack-water bay stage will migrate along the lagoon toward the source of longshore débris, i.e., the headland. This space relationship of the idealized stages will be discussed again with reference to the New Jersey shoreline.

THE TEST OF THE THEORY

A test of the foregoing theory must be made by study of typical, young shorelines of emergence upon which lagoon deposition has proceeded far enough to support tidal marshes. Tidal lagoons in which no marsh is present are too young to be considered; also, those lagoons which are entirely filled and devoid of any telltale pattern of channels or bays are too old to serve as a test of the theory. The best example of a shoreline well suited for such a test is that of New

Jersey, south of Bay Head. In the absence of contradictory evidence, the postulates of tidal inlet behavior are assumed to hold true, as Johnson[8] used this same shoreline to establish their validity.

Only local areas of the New Jersey shore are used to test the theory. The complete shoreline may be studied by reference to U.S.

FIG. 5.—Barnegat Inlet area showing symmetrical tidal deltas

Coast and Geodetic Survey Charts Nos. 1216, 1217, 1218, and 3243. Barnegat Inlet, near the northern (headland) end of the lagoon, is shown in Figure 5. The tidal delta and marsh islands are quite similar to Figure 1, either *C*-1 or *A*-1. Figure 6 is farther south along the same lagoon. At Beach Haven Inlet and Little Egg Inlet the close spacing of the inlets and the great width of the lagoon results

[8] *Op. cit.*, pp. 370–72.

in deposition in the lagoon as though from a single inlet. The stage is probably early delta bay, as at *C*-2 or *A*-3 in Figure 1. Little Egg Harbor and Great Bay are fairly symmetrical and about equidistant

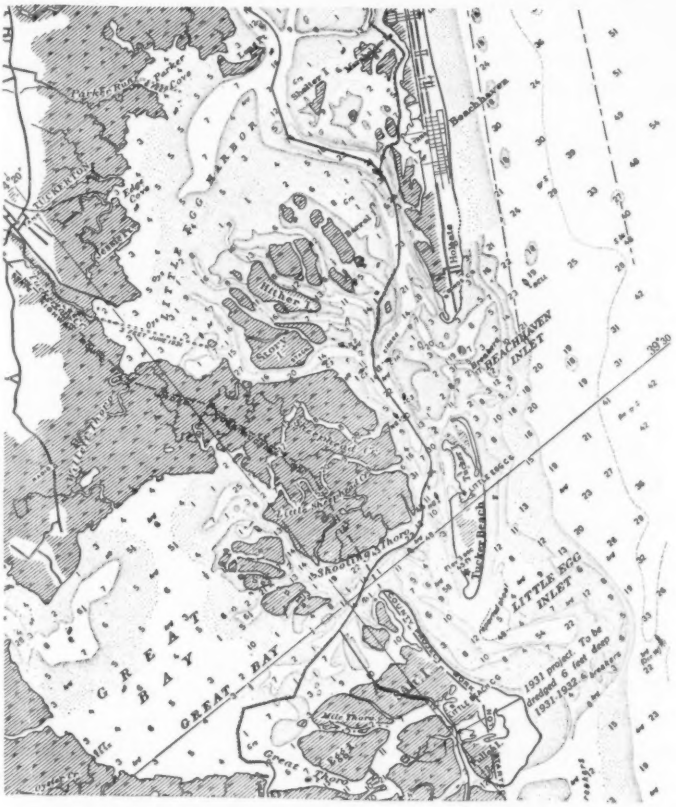


FIG. 6.—Little Egg–Great Bay area, illustrating the "early delta bays"

from the inlet, considering the double inlet as one, corresponding to the deduced conditions for "delta bays."

At Absecon Inlet (Fig. 7) two more delta bays—Read and Absecon bays—are well developed. The stage is about that of *B*-2 (Fig. 1), and the deltaic character of the distributary marsh channels is un-

mistakable. Absecon Inlet appears to be slightly south of the center of the delta, as though a slight, recent migration of the inlet had taken place after a long, stationary period of delta-building. Indeed, the inlet was nearly a mile north of its present position in 1877, according to a U.S. Coast and Geodetic Survey chart of that year.

South of Atlantic City the lagoon narrows abruptly, and a corresponding jump in the stage of deposition should occur. Townsend

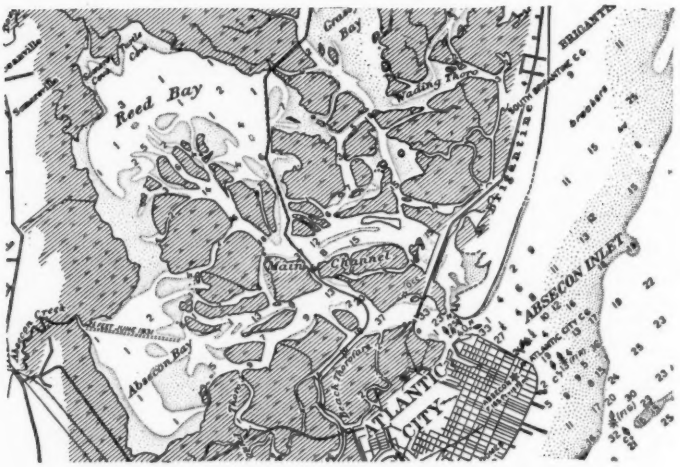


FIG. 7.—Absecon Inlet with its pair of "late delta bays"

Inlet (Fig. 8) still exhibits a definite delta marsh separating two very late delta bays—Stites Sound, and Townsend Sound. This inlet also has migrated southward a short distance in recent years, as indicated by its position south of the center of the old delta. The slack-water bay of Great Sound is symmetrical to a marked degree in both shape and position. This bay, close to the small delta bays at Townsend Inlet, shows that both slack-water bays and delta bays may exist at the same inlet, but that the slack-water bay is the last lagoon feature to be preserved. Conditions at Hereford Inlet are not clear, with the exception of the deltaic character of the channels connecting Jenkins sound to the inlet. If, as seems likely, this was the ancient delta, then this inlet also has migrated slightly southward in recent years.

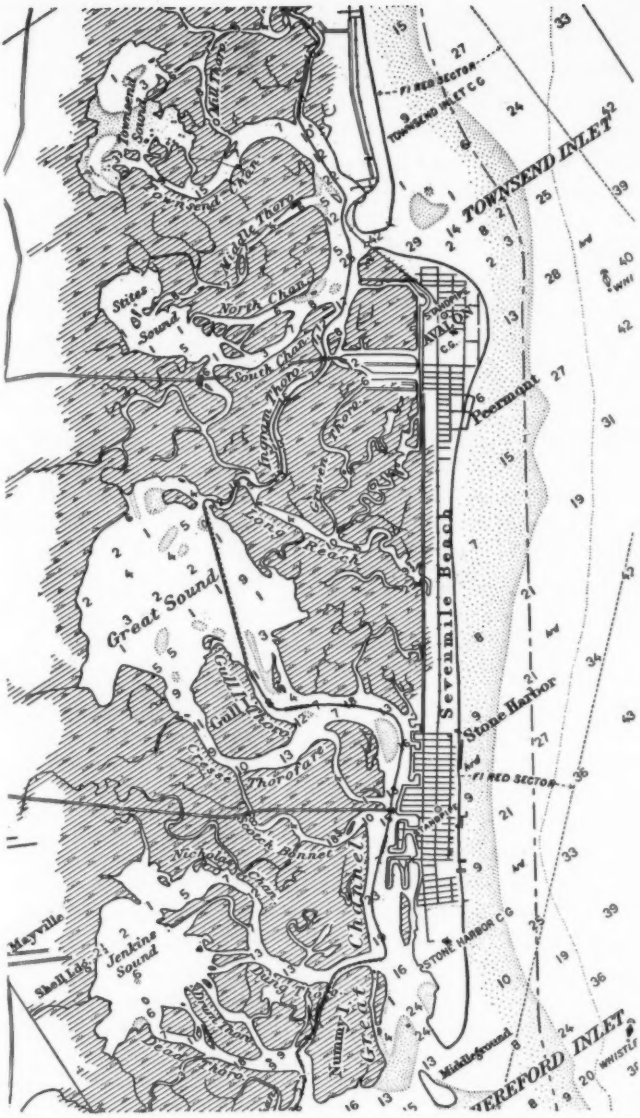


FIG. 8.—Townsend-Hereford area, showing very small "delta bays" at Townsend Inlet and a "slack-water bay," Great Sound, midway between inlets.

Farther south the lagoon becomes very narrow (Fig. 9), but a few indications of lagoon history are still preserved. Richardson Sound and Jarvis Sound are both shaped like the ideal slack-water bays but are not in the logical position with respect to inlets. Instead of being midway between the inlets, they are both between the same two inlets. If an inlet once existed about midway between these two sounds, they would be perfect examples of the deduced slack-water bays. Assuming the former presence of such an inlet, the marsh pattern in the lagoon should afford indications in support of the extinct inlet. Examination of the marshes west of Wildwood and Wildwood Crest (Fig. 9) shows a radial pattern of marsh channels still preserved. These channels converge in a small bay, Sunset Lake, just west of the barrier beach, as though they had once led to an inlet which has since been closed by the longshore currents. Records show that Turtle Gut Inlet existed at this point less than ten years ago, separating Two Mile beach from Five Mile beach. Thus, the suggestive bays and the old delta channels both serve, in this case, as evidence useful in interpretation of inlet history. The part played by longshore currents from the headland in closing extinct Turtle Gut Inlet is evident in the extreme width of the beach north of the Cape May Harbor jetties.

The investigation of the New Jersey shoreline affords definite confirmation of the theory of an orderly evolution of lagoon deposits, despite the likelihood of other factors complicating the situation. With but few exceptions, the pattern of shoals and marshes at each inlet has its counterpart, greatly simplified, in the idealized evolutionary stages.

It is recognized that the New Jersey lagoon varies greatly in width; that the distance between two inlets varies from 1 to 20 miles; that the inlets are by no means of equal cross section; that incoming rivers carry detritus and produce currents which may drastically alter the lagoon deposits; and that the present condition of channels and inlets is affected to a great extent by structures and activities of man. When these and other factors which may affect the lagoon are considered, the New Jersey shoreline provides a remarkably successful test of the theory of evolution of lagoon deposits on shorelines of emergence.

The arrangement of the ideal stages with respect to the headland

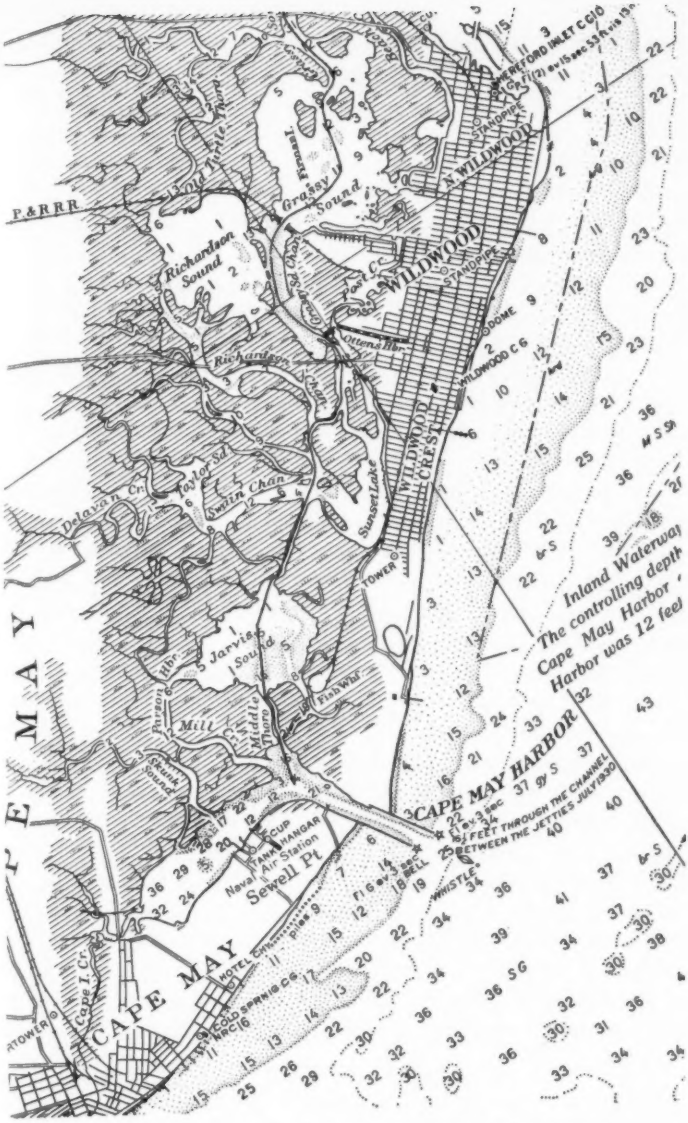


FIG. 9.—Cape May area, showing the latest stage in lagoon deposition

is precisely what is expected if the stages of deposition conform to the deductions presented previously under space and time relations. At Cape May (Fig. 9), where the lagoon narrows and finally ends, the marsh is well developed and the deduced slack-water bay stage is present between four consecutive pairs of inlets, going toward the headland. In Figures 8, 7, 6, and 5, respectively, examples are seen of the late delta bay, the early delta bay, and the marsh island stages until, at Barnegat Inlet, nearest the headland, the best tidal delta is built. The logical order of these events is attained to a marked degree. It is believed that the fifth, or slack-water bay, stage will proceed toward the headland until Barnegat Inlet itself has reached this stage. The lagoon then will be nearly completely filled and the depositional history will draw to a close.

Figures 5, 6, 7, 8, and 9 may bring to mind the foregoing discussion of the conflict between greater deposition near the headland and more rapid lagoon-filling far from the headland. It is believed that longshore débris, moving southward from Barnegat Inlet, becomes less in quantity because of the deposition of material in the lagoon at each inlet encountered. The difference in material carried to successive inlets, however, is not believed to be great. The reasons why the quantity of longshore débris is believed to decrease slowly are: (1) the larger the size of the bay drained by an inlet, the more rapid will be the tidal currents at that inlet; (2) the rapid tidal currents will carry much débris, but the velocity of the ebb always exceeds that of the flood, so that delta building is very slow; (3) far from the headland inlets are numerous, and the more constant salinity favors marsh growth, (4) which aids in deposition of silts and clays which do not occur in any great quantity near the headland. Thus, the lagoon near Cape May may receive less sediment than Barnegat Bay, but deposition is still rapid and the lagoon so narrow that it is filled much faster than Barnegat Bay, where the great tidal delta is built. The same phenomenon is illustrated on Long Island, where the narrow part of the lagoon near East Rockaway Inlet is nearly filled, but the delta at Fire Island Inlet is the largest on that shore.

LONG ISLAND

The south shore of Long Island is also considered a good example of a young shoreline of emergence, even though it has been affected somewhat by the outwash plain from the Wisconsin terminal mo-

raine. Figure 10 shows the first inlet away from the headland, Fire Island Inlet, with its great offset and overlap suggesting rapid westward migration. The lagoon deposits confirm this suggestion and correspond to *A*-2 in Figure 3. Both the shape of the elongated tidal delta and its asymmetrical position with regard to the inlet indicate rapid migration of the inlet.

Proceeding westward, the next inlet, Jones Inlet, should approximate conditions at *A*-3 or *A*-4 in Figure 3, but the lagoon deposits are complex and the ideal pattern is obscured. The entering channel does parallel the eastward point of the barrier beach and the distributary channels are transverse to the lagoon. The marsh has little symmetry or regularity of pattern, but this is precisely what was expected if the inlet has migrated rapidly away from the headland.

Long Island also appears to confirm the theory, although the number of tests is small. It is likely that Great South Bay will slowly fill from the westward end and that Fire Island Inlet will deposit sediments in the lagoon in a manner similar to the idealized stages of Figure 3.

Other shorelines should serve as tests of the theory; but no other shoreline, of which good charts are available, is regarded as a typical young shoreline of emergence with partial deposition in the tidal lagoons. Between Delaware and Chesapeake bays a few slack-water bays are poorly developed. So many features of a complicating nature may be present to offset the delicate balance of conditions necessary to the development of the deduced evolution, however, that the theory cannot definitely be confirmed on the other shorelines of the Atlantic seaboard. The Virginia coast does not show the expectable inlet behavior, "probably as a result of an exceptionally flat sea floor which permitted the bar to form far offshore."[9] The "sea isle" section of the Carolina coast has had a complicated history and may never have developed the typical offshore bar and tidal lagoon. The Florida coast has had the normal history confused by coquina and coral growth.

VALIDITY OF THE THEORY

Although this conception of the evolution of lagoon deposits on shorelines of emergence is not clearly confirmed on all such shorelines, it is believed that the shores of New Jersey and Long Island

[9] Johnson, *ibid.*, p. 372.

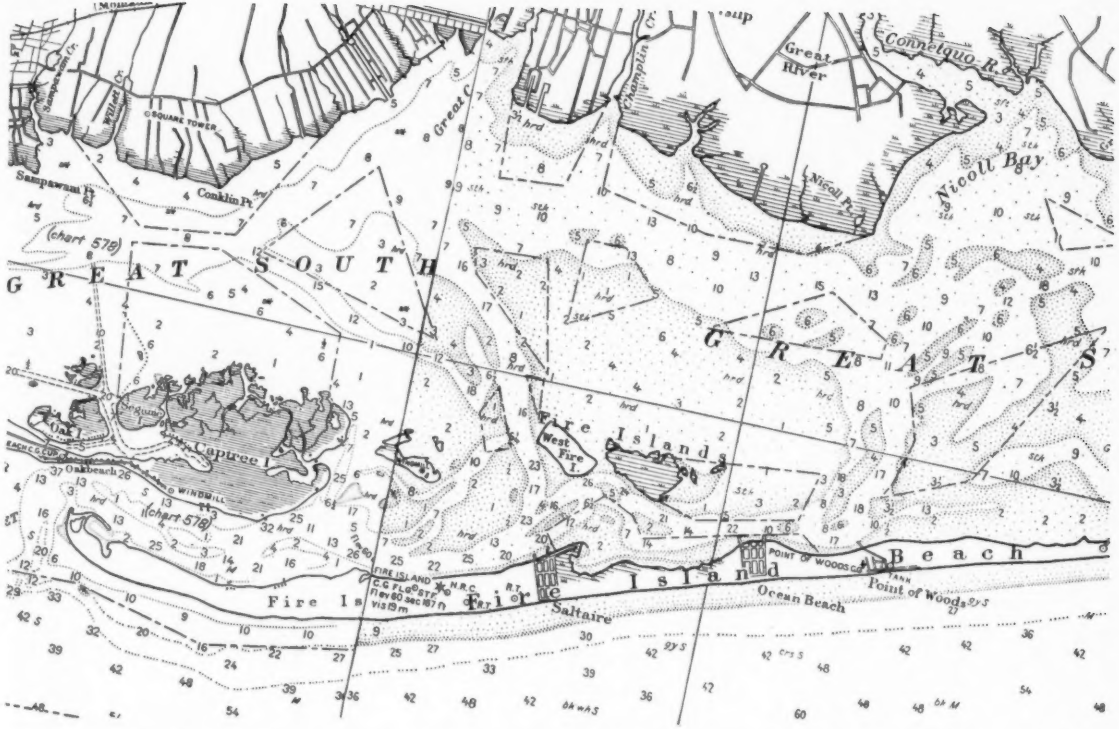
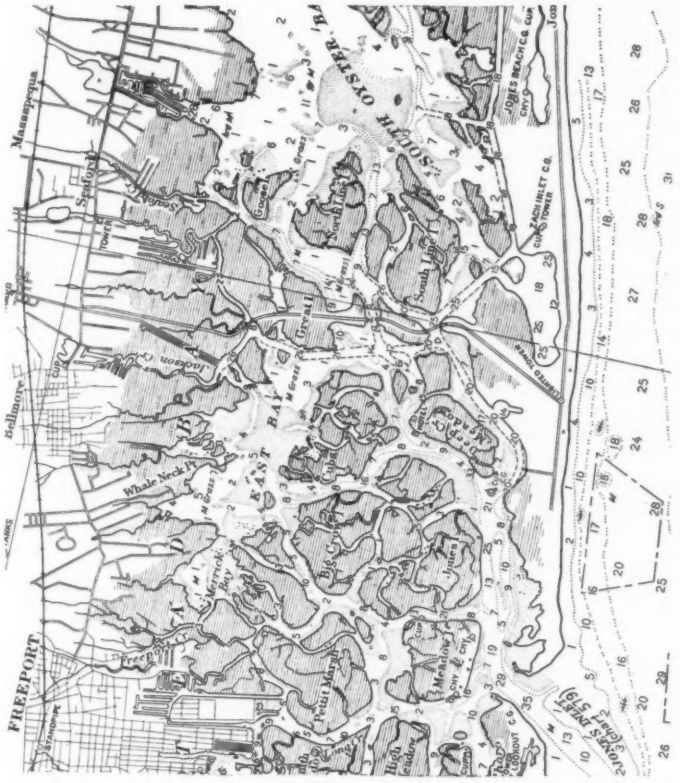


FIG. 10.—Fire Island Inlet, showing extreme asymmetry due to rapid inlet migration. (Taken from U.S. Coast and Geodetic Survey charts nos. 1214 and 1215.)

afford sufficient confirmatory evidence to warrant its consideration as a working hypothesis. The abundance of factors which may disturb the operation of the principle that lagoon deposits are an ex-


OYSTER BAY
SOUTH
EAST BAY
Massapequa
Seaford
Bellmore
Jackson
Whale Neck Pt.
FREEPORT
Merrick Bay
Petit Marsh
Meadow
Hugh Gaddis
Jones Inlet
Zachariah Conk
Tower
Lighthouse
Coast Guard Station
Channel
Shoal
Rock
Wreck
Spoil Area
Ch.
Cut
Jetty
Groin
Bulkhead
Pier
Dock
Marsh
Creek
Inlet
Bay
Point
Beach
Dune
Sand
Gravel
Stone
Concrete
Wood
Steel
Iron
Brick
Tank
Flagpole
Radio
Antenna
Power Line
Telephone
Road
Trail
Railroad
Bridge
Building
Church
School
Cemetery
Water
Land
Swamp
Woods
Grass
Sand
Mud
Rock
Shell

UTILITY OF THE THEORY

If, as seems to be the case, inlet history sometimes leaves records in the pattern of lagoon deposits, a chart representing such deposits may indicate the inlet history. For example, if migrating inlets deposit tidal deltas as thickening wedges (Fire Island Inlet), rather than as arcuate fans (Barnegat Inlet), then the delta form should constitute evidence for rapid inlet migration. If the lagoon deposits correspond to the deductions in Figures 1 and 2, then these lagoon features should be recognized as indications of great stability of the inlets.

As previously stated, many New Jersey inlets have tidal deltas and delta bays so symmetrical that they were probably produced by stationary inlets, but the inlets at present are not at the center of their delta deposits. The interpretation of a long period of stability, followed by a recent, short period of migration was offered for such features. This interpretation agrees closely with records on old coast charts, and a similar history was demonstrated for Barnegat Inlet, based upon actual field evidence.[10]

CONCLUSIONS

A theory of evolution of lagoon deposits is presented, and is shown to be in accord with the facts observed at Barnegat Inlet and also with the laws believed to govern tidal inlets in general.

The many New Jersey and Long Island inlets which confirm the deduced evolution lead to the belief not only in its validity but also in the truth of the laws of tidal inlets. The idealized lagoon stages may exist at the same time on a single coast if the lagoon is long enough, but each segment of such a lagoon will probably pass through all five of the hypothetical stages of evolution as time goes on. Many of the lagoon features on the New Jersey and Long Island shores are extremely useful in the interpretation of inlet history. The interpretations offered are invariably confirmed by a study of chart and field evidence.

The writer believes that the application of the theory to other shorelines should augment the knowledge of shore processes and reveal much of the shoreline history where other records are inadequate.

[10] John B. Lucke, "A Study of Barnegat Inlet, New Jersey, and Related Shoreline Phenomena," Shore & Beach, Vol. II, No. 2, Chap. iii.

THE MINOR CHEMICAL CONSTITUENTS OF SOME IGNEOUS ROCKS[1]

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ABSTRACT

The investigation is concerned with the spectrographic identification of those elements occurring in igneous rocks in quantities of less than 1 per cent. Identification has been facilitated by the preparation of standard powders containing certain elements in known amounts ranging from 1 per cent to 0.0001 per cent included in a base of typical granite. By comparison, these standards afford a means of making a rough estimate of the amount of a minor constituent giving lines in a spectrogram.

As a basis for the comparison of a number of igneous rocks, a granite from eastern Ontario was studied in detail. Then the minor constituents were determined in fourteen granites from widely separated localities ranging in age from Algoman to Devonian.

INTRODUCTION

A very close relationship between certain types of ore deposits and intrusions of igneous rocks seems evident. Unfortunately, observations are limited to the final products of the evolution of the magma, and the processes that were operative in earlier stages can only be inferred. The orderly nature of crystallization that seems to have occurred in igneous rocks indicates a possible process of concentration of some constituents, but ore bodies are commonly found not in the igneous masses to which they are genetically related but around their margins in the older rocks. If the elements of the ores were originally in the magma from which the igneous bodies crystallized, they must have been collected by some agency, since most of them are present in igneous rocks only in minute quantities. Concerning this process of concentration there are many problems. Are all primary deposits formed by a single process, or are there a number of processes such as immiscibility of sulphides, immiscibility of an aqueous solution containing the metals, crystal settling, gas transfer and concentration in a liquid residue by crystallization, each capable of giving rise to an ore deposit under certain conditions? Does some such process invariably operate during the slow cooling and crystal-

[1] This paper is based on work carried out with the aid of a scholarship granted by the National Research Council of Canada, Queen's University (1931–32).

lization of a magma, or is it entirely lacking in some cases? Must the parent magma contain a larger than normal proportion of the ore metals for the formation of ore deposits? To what degree are those metals which are found in traces in igneous rocks characteristic of the associated ore deposits?

Whether or not all magmas of a similar type contain the same quantities of the elements of a certain ore, it seems unlikely that any method of concentration could completely remove these elements from that portion which crystallizes as the igneous rock associated with the ore.

If it be true that some magmas contain a greater proportion of the metals than others, it is equally likely that other relatively rare elements may vary from one intrusive to another, thus yielding a recognizable characteristic which could be used to identify the intrusive and aid in correlation.

It is evident that a great mass of data must be obtained before any general conclusions can be drawn as to the likelihood of the occurrence of ore deposits associated with a particular intrusive.[2]

SPECTROGRAPHIC INVESTIGATION

An E 316 Hilger quartz spectrograph was used in the spectrographic work. With this instrument it is possible to photograph the spectrum between 8000 A and 2000 A on a 10-inch plate. The width of this plate is 4 inches, which allows twenty-one exposures. An internal wave length scale is provided, and a Hartmann diaphragm with three openings makes it possible to compare three spectra thrown into close juxtaposition.[3]

For the purpose of spectrographic analyses, rock specimens were crushed in a steel mortar to −100 mesh Tyler, and samples of this powder were placed in a direct current arc. Electrodes of both copper and carbon were used.

[2] The writer wishes to express his indebtedness to Dr. E. L. Bruce, under whose direction this investigation was carried out, for the use of laboratory equipment and for criticism and suggestions during the progress of the investigation. Sincere thanks are also extended to Professor J. K. Robertson for initiation into the technique of spectroscopy, for valuable suggestions, and for encouragement in this work.

[3] This equipment with accessories for spark and arc excitation, development, and examination of plates is fully described in bulletins published by A. Hilger, Ltd.

In order to make certain of the most persistent lines of the elements sought[4] and to make possible the rapid examination of a large number of specimens, a series of standard powders was prepared containing 1 per cent, 0.1 per cent, 0.01 per cent, 0.001 per cent, and 0.0001 per cent of these elements. A large supply of uniform granite crushed to 100 mesh and thoroughly mixed so as to provide a uniform material was used as a base for the preparation of these standards. The procedure was as follows:

To 95.05 grams of granite 4.95 grams of $Co(NO_3)_2 \cdot 6H_2O$ were added and ground in an agate mortar. This was mixed first by rolling on paper, then by grinding in a small flint ball mill for an hour, and finally by more rolling on paper, during which process the sample was reduced by quartering to approximately 5 grams. From this sample small amounts were taken as required and placed in the arc.

Similarly, 1 per cent standards containing P, Zr, Mn, Ba, Sr, Mo, Bi, B, and Zn were made up. Ten grams of each of these ten standards were then selected by sampling and combined. This material was mixed, ground for an hour, and quartered down to 5 grams.

A second series was started containing 1 per cent and 0.1 per cent of Pb, Ni, V, Hg, Ag, Cr, Sn, Sb, and Th. These two series were then combined to give 0.1 per cent, 0.01 per cent, 0.001 per cent, and 0.0001 per cent of these twenty elements.

INTENSITY OF SPECTRAL LINES

In estimating the intensity of the persistent lines given by the standard powders, values were assigned ranging from 1 to 10. This scale is not absolute in any respect; on the contrary, it depends entirely on personal observation. An intensity of 10 was given to the strongest persistent line of any minor constituent found in the 0.1 per cent standard spectrum and 1 was given to a line of approximately one-tenth this intensity. An intensity of 1 is easily recognized, once a standard has been accepted. For this purpose the line (Mn)2794.82 A, as developed in one particular spectrum, was constantly referred to.

[4] The recently published edition of *Wavelength Tables for Spectrum Analysis*, by F. Twyman and D. M. Smith, published by A. Hilger, which contains a list of persistent arc lines, was not available until this investigation was nearly completed.

This method of indicating intensities is not susceptible of very great accuracy; but where a number of lines were in the field of vision at one time, the relative intensities of the lines could be estimated with considerable assurance. For this reason, the figures in each horizontal row of the tables giving the intensity of persistent lines of standard powders may be considered as representing fairly accurately the relative intensities of these lines. With regard to the comparison of lines in different parts of the spectrum, and in different spectra, the writer believes that comparisons of lines ranging in intensity from a trace to 3 are fairly accurate. Above this the intensities are more difficult to estimate. It is always problematical whether a line should be designated 6 or 7; but with a standard of 1 firmly fixed in mind, there is no doubt between 2 and 3.

Aside from the personal equation in the comparison of two spectra, the equivalence with regard to conditions of excitation, exposure, and developing must be considered before an accurate comparison can be made.

UNIFORMITY OF ARC CONDITIONS

Uniformity of arc conditions was striven for throughout the investigation, since uniform spectra are essential for even an approximate quantitative estimate of the amount of an element by a comparison of the intensity of spectral lines. This is particularly true when the comparison is made from one spectrogram to another.

The intensity of arc illumination varies with the current employed, the arc length, and the composition of the electrodes, including any introduced substance. These factors can be controlled, at least partially; and when copper electrodes were used, the results were fairly uniform. Variations do result, however, due to vagaries of the arc discharge. Wandering of the discharge from one part of the electrode to another is the cause of very great fluctuations in the intensity of illumination.

The intensity of the aluminium lines at 2568.00 A and 2575.11 A, and the intensity of the bands due to silicon were used as internal standards to determine which spectra of granite and of standard powders were comparable.

For the preparation of the following tables showing the variation

of persistent lines with decreasing concentration of the elements listed, five series were made before one was obtained with six comparable spectra of the carbon arc in close juxtaposition. Only two were made of the copper arc, and both were satisfactory.

When spectra of material unlike in composition were compared, real difficulty was encountered in deciding which spectra were truly equivalent. In judging the spectra of the specific-gravity fractions, the rough mineralogical analysis given below was referred to, and this aided considerably in a decision.

The intensity of a spectrum may be judged approximately by the density of the continuous spectrum or darkening of a plate between spectral lines. In seeking the optimum conditions for detecting the minor constituents, it was found that too long exposure, or too intense a spectrum, resulted in a masking of faint lines of the minor constituents; and conditions just under this point were selected. For this reason it seems unlikely that the minor constituents have been overestimated.

THE ARC SPECTRA OF STANDARD POWDERS

The standard powders eliminated the uncertainty with regard to persistent lines and made it possible to pick out lines due to a particular element, and to follow the decrease of their intensity down to that resulting from a content of 0.0001 per cent, or until the lines disappeared. When a minor constituent was spectroscopically present in the base material, this fact was brought out by the persistence of one or more of its lines as the concentration of the element was diminished. Further, by noting the concentration below which decrease in intensity of the spectral lines cannot be recognized, an estimate can be made of the amount of the minor constituent present. Thus, in Table I the addition of 0.0001 per cent Ba to the base material did not increase the intensity of the spectral lines. Neither did 0.001 per cent Ba; but 0.01 per cent produced a large effect, and it may be concluded that the barium content of the base material lies between 0.001 per cent and 0.01 per cent.

Over one hundred and fifty spectra of standard powders were examined, and these had a remarkably uniform appearance. In every one, the persistent lines that should occur were found; and,

TABLE I

CARBON-ARC SPECTRUM OF STANDARD POWDERS*
VARIATION OF INTENSITY OF PERSISTENT LINES WITH DECREASING CONCENTRATION OF AN ELEMENT

ELEMENT	WAVE LENGTH	PERCENTAGE				BASE	CARBON ELECTRODES
		0.1	0.01	0.001	0.0001		
Ba	4554.04	8	8	2	2	2	.....
	3501.1	2	2	0.2	0.2	0.2	.....
Sr	4607.34	8	8	2	2	2	.....
	4077.71	9	8	2	2	2	.....
Mn	2801.08	4	3	2	2	1	3
	2798.27	4	3	2	2	1	3
	2794.82	4	3	2	2	1	3
Zr	3391.98	4	3	0.5	0.2	0.2	.....
	3496.21	2	2	.....	.....	.....	.....
B	2497.73	3	2	2	2	2	3
	2496.78	2	1	1	1	1	2
Mo	2816.18	.....	.....	.....	.....	.....	.....
	2775.4	0.5	0.5	.....	.....	.....	.....
Cr	3605.33	8	8	2	1	0.5	.....
	3593.48	8	8	2	1	.....	.....
V	3185.41	3	2	0.2	Tr	Tr	.....
	3183.99	3	2	0.2	Tr	Tr	.....
	3183.42	3	2	0.2	Tr	Tr	.....
Pb	2833.07	2	2	0.5	Tr	Tr	Tr
	2614.20	2	2	0.1	.....	.....	.....
Sn	2863.32	2	2	0.5	Tr	Tr	Tr
	2839.99	2	2	0.5	Tr	Tr	Tr
Co	3453.51	4	4	.....	.....	.....	.....
	3405.12	3	3	0.2	.....	.....	.....
Ni	3414.77	4	4	0.5	.....	.....	.....
	3515.06	2	2	.....	.....	.....	.....
Sb	2598.08	1	1	0.5	.....	.....	.....
	2311.50	.....	.....	.....	.....	.....	.....
Bi	3067.73	1	1	.....	.....	.....	.....
	2897.98	1	1	.....	.....	.....	.....

* In dealing with lines due to very small percentages of an element, it was found necessary to subdivide an intensity of 1 into ½, ¼, and ⅛, in each case halving the intensity. In the tables these fractions have been simplified to 0.5, 0.2, and 0.1, to facilitate typesetting. The term "trace" (Tr) was applied to a disturbance in the background of a plate which was undoubtedly due to the element indicated but was too indistinct to be accurately measured with the micrometer.

TABLE I—*Continued*

Element	Wave Length	Percentage				Base	Carbon Electrodes
		0.1	0.01	0.001	0.0001		
Zn	3345.51	1	1	.....	.....	.....	.....
Cd	3610.51	0.5	0.5	.....	.....	.....	.....
	3261.05	0.5	0.5	.....	.....	.....	.....
Ag	3280.67	6	5	2	0.2	0.2	.....
	3382.89	5	4	1	0.1	0.1	.....
Hg	2536.52	0.5	0.5	.....	.....	.....	.....
Th	4019.14	0.2	0.2	.....	.....	.....	.....
	3601.05	0.2	0.2	.....	.....	.....	.....

since the important lines appear to be of the same intensity on the various plates, it is assumed that the mixing of the powders was sufficiently thorough to give a uniform product, even in a sample as small as 0.05 grams.

The carbon and copper-arc spectra of these powders are in general agreement; but there are many small differences, such as that in the intensity of the spectrum of a particular element, or the slightly different relative intensity of individual lines. The most striking contrast is the entire absence of any lines due to barium or strontium in the copper-arc spectrum; whereas the carbon-arc spectrum shows strong lines for both these elements.

It will be noticed in Table I, which shows the variation of intensity of a few of the persistent lines of each element sought, that manganese and boron are present as impurities in the carbon electrodes in percentages of approximately Mn, 0.01 per cent, B, 0.1 per cent. In spite of this, the intensities of the manganese and boron lines decrease with decreased concentration in the powders; and it is apparent that the powders exert a blanketing effect on the spectrum of the impurities in the electrodes. This fact has been repeatedly observed, not only with the impurities in the carbons but also with the lines of copper, many of which weaken or disappear when a powder is introduced into the copper arc. For this reason it seems likely that tin and lead are minor constituents of the granite used as a base for the

TABLE II

COPPER-ARC SPECTRUM OF STANDARD POWDERS

VARIATION OF INTENSITY OF PERSISTENT LINES WITH DECREASING CONCENTRATION OF AN ELEMENT

ELEMENT	WAVE LENGTH	PERCENTAGE				BASE	COPPER ELECTRODES
		0.1	0.01	0.001	0.0001		
Ba							
Sr							
Mn	2801.08	3	2	0.5	0.5	0.5	
	2798.27	3	2	0.5	0.5	0.5	
	2794.21	3	2	1	1	1	
Zr	3391.98	3	2	0.1	0.1	0.1	
	3496.21	3	2	0.1			
B	2497.73	4	3	0.5	0.5	0.5	
	2496.78	3	2	0.2	0.2	0.2	
Mo	2816.18	2	1				
	2775.4	1	0.5				
Cr	3605.33	8	6	2	1	0.2	
	3593.48	10	9	3	1		
V	3185.41	4	3	1	0.5	0.2	
	3183.99	4	3	1	0.5	0.2	
	3183.42	4	3	1	0.2	0.1	
Pb	2833.07	4	3	1	0.5	0.1	
	2614.20	3	2	0.5	0.2	0.1	
Sn	2863.32	3	2	0.5	0.2	0.1	Tr
	2839.99	4	3	1	0.5	0.2	0.2
Co	3453.51	2	1				
	3405.12						
Ni	3414.77	4	2	0.5			
	3515.06	2	1	Tr			
Sb	2598.08	2	1				
	2311.50	1	0.5				
Bi	3067.73	4	3	Tr			
	2897.98	2	1				
Zn	3345.51	3	2				

TABLE II—*Continued*

Element	Wave Length	Percentage				Base	Copper Electrodes
		0.1	0.01	0.001	0.0001		
Cd	3610.51	1	0.5	0.5	.....	.....	.....
	3261.05	0.5	0.5	.....	.....	.....	.....
Ag	3280.67	*					
	3382.89	*					
Hg	2536.52	0.5	0.1	.....	.....	.....	.....
Th	4019.14	*					
	3601.05	.....					

* Copper lines occur here.

standard powders, although the lines for those elements are as strong in the spectrum of the carbons alone as they are when the rock powder is present. The presence of Mn, B, and Pb has been established by use of copper electrodes which do not contain these elements. The presence of tin has been confirmed by the use of carbons which do not contain this impurity and also by the study of heavy fractions of the granite. Similarly, the presence of chromium, vanadium, and silver has been confirmed. Zircon is known to occur from mineralogical examination of the granite.

MICROSCOPIC EXAMINATION OF AN EASTERN ONTARIO GRANITE

Eight specimens of granite were collected in a distance of 100 feet along a north-south line across a granite quarry on the south side of the main highway, Lot 20, Concession 2, Township of Lansdowne, County of Leeds, Ontario. The quarry is centrally located in a large granite area mapped by Wright[5] as middle or late pre-Cambrian. The granite is pink in color. The larger feldspar grains are 3 mm. across, but in thin section the average size of the feldspar is 0.5 mm; the quartz grains are slightly smaller, 0.3 mm. The minerals recognized under the microscope are: quartz, microcline, orthoclase, microcline-perthite, perthite, muscovite, biotite, magnetite, zircon, apatite, chlorite, and sericite.

[5] J. F. Wright, "Brockville-Malorytown Map-Area, Ontario," *Geol. Surv. Can., Mem. No. 134* (1923), pp. 32–33.

Using an objective of high power, the quartz appears crowded with inclusions of hairlike crystals, presumably rutile, gas cavities, and a great number of black to reddish specks far too small to be determined. It also contains a few crystals of apatite and zircon.

The feldspars are somewhat altered and are clouded so that only the larger inclusions are visible The rutile needles so common in the quartz were not noticed, but scattered apatite and zircon crystals are to be seen. Microcline is the most abundant feldspar.

Muscovite and biotite occur only as a few small fragments.

Chlorite is more abundant and probably represents original biotite crystals. It constitutes 1–2 per cent of the rock.

Magnetite occurs in grains of 0.15 mm. and less in diameter. It is more abundant in the feldspars than in the quartz. Magnetite is estimated to form 1 per cent of the rock.

HEAVY SOLUTION SEPARATION OF LANSDOWNE GRANITE

An aqueous solution of potassium mercuric iodide (Thoulet solution) which has a maximum specific gravity of 3.196 was used in making the separation. A sample was crushed and sieved. The sieve fraction −40+100 mesh was found to be the coarsest material in which the minerals occur as individual grains, and it was used with the following solutions:

Specific Gravity of Solution	Fraction	
	No.	S. G.
2.945	1	>2.945
2.680	2	>2.680
2.640	3	>2.640
2.612	4	<2.612
2.628	5	>2.628
2.630	6	>2.630
2.630	7	<2.630

A magnetic separation of fraction No. 1 was made, giving 5 fractions:

No. 8.—Highly magnetic foils of metallic iron derived from the crushing machinery.

No. 9.—Magnetite with small amounts of adhering quartz and feldspar.

No. 10.—Slightly less magnetite than No. 9.

No. 11.—Quartz and feldspar with small specks of adhering magnetite.

No. 12.—Non-magnetic. Quartz and feldspar with about 5 per cent apatite and zircon fragments.

A microscopic examination of the specific-gravity fractions gave the following compositions:

No. 2.—Quartz and feldspar with adhering magnetite.

No. 3.—Feldspar, 80–90 per cent. Only the variety perthite was recognized. The remainder of the fraction was quartz with a few scattered fragments of apatite.

No. 4.—Feldspar, 90–95 per cent. In order of abundance these were: microcline, perthite, and microcline-perthite.

Quartz, 5–10 per cent.

No. 5.—Quartz, 5–10 per cent, the remainder in order of abundance being perthite, myrmekite, and microcline.

No. 6.—Quartz, 60 per cent approximately.

Perthite, 40 per cent approximately.

No. 7.—Quartz, 60 per cent approximately, the remainder being perthite with some myrmekite.

It was found impossible to obtain a fraction containing only one mineral, but from the most concentrated fractions it was possible to separate the grains under the microscope with the aid of a needle. In this way a supply of quartz was picked out of fraction No. 6 and microcline grains were picked out of fraction No. 4.

THE MINOR CONSTITUENTS OF LANSDOWNE GRANITE

The minor constituents of four specimens of Lansdowne granite are listed in Table III, and intensities are given on the same scale as used previously. The spectrum of each sample was compared directly with that of the 0.01 per cent standard powder.

The minor constituents of the specific-gravity fractions have been listed in Tables IV and V. In examining these tables it is to be borne in mind that the fractions are not composed of single minerals, although in most of them a particular mineral is predominant.

Fraction No. 8 consists largely of foils of metallic iron with fine particles of magnetite and other minerals adhering, and should be disregarded, so far as the mineralogical distribution of the minor constituents is concerned. It contains very few of the minor con-

stituents recognized in the granite, except chromium; and so it is unlikely that steel from the crushing machinery has influenced the results of the analyses of the granite fractions.

TABLE III

THE MINOR CONSTITUENTS OF LANSDOWNE GRANITE AND THEIR INTENSITY IN THE ARC SPECTRUM

Specimen No.	Intensity in the Arc Spectrum									
	Ba	Sr	Mn	B	Cr	V	Sn	Pb	Ag	Co
1	3	3	0.5	0.5	.....	.1	.....	.....	1	.....
6	0.5	0.5	0.5	0.5	Tr	Tr	.....	.....	1	.....
7	2	3	2	0.5	Tr	0.5	Tr	Tr	0.5	1
8	2	2	0.2	0.5	.....	0.5	.....	.....	1	.....

Lead and silver are concentrated in more than one fraction and probably occur in more than one way. Lead may occur as galena in the non-magnetic fraction and as an impurity in a magnetic mineral. It may be present in zircon, biotite, etc., as a residue of radioactive disintegration. Silver may be present as an impurity in quartz, microcline, and a ferromagnesian mineral, as well as native.

TABLE IV

THE MINOR CONSTITUENTS OF SPECIFIC-GRAVITY FRACTIONS OF LANSDOWNE GRANITE

No.	Specific Gravity Fraction	Intensity in the Arc Spectrum									
		Ba	Sr	Mn	B	Cr	V	Sn	Pb	Ag	Co
4	<2.612	2	2	0.2	.....	0.2	.....	Tr	0.5	3	.....
5	>2.628	0.2	.....	1	0.5	.....	.....	0.2	0.5	1	.....
7	<2.630	0.5	1	1	0.5	0.2	.....	0.5	.....	0.2	.....
6	>2.630	0.5	0.5	0.5	Tr	.....	.....	.....	.....	1	.....
3	>2.640	0.2	0.5	1	0.2	0.2	Tr	.....	0.2	0.5	.....
2	>2.680	0.5	0.5	1	0.5	0.2	0.5	0.5	0.5	0.5	.....
12	>2.945	.....	.....	1	0.2	0.2	1	1	2	4	.....
	Quartz	.....	.....	.....	.....	1	Tr	.....	Tr	4	.....

THE MINOR CONSTITUENTS OF SOME PEGMATITE MINERALS

Specimens of a few pegmatite minerals were collected from the feldspar pits west of the village of Verona, in Lot 16, Concession 10, Portland Township, Frontenac County, Ontario. The pegmatite

TABLE V

THE MINOR CONSTITUENTS OF FRACTIONS FROM THE MAGNETIC SEPARATION OF HEAVY MINERALS

No.	Distance from Magnet in Cms.	Intensity in the Arc Spectrum									
		Ba	Sr	Mn	B	Cr	V	Sn	Pb	Ag	Co
11	0.00	1	.....	1	2	2	2	1	1	5	.....
10	0.25	.....	.....	3	0.5	2	2	2	2	3	.....
9	0.50	.....	.....	0.5	0.2	2	2	0.2	1	0.2	.....
8	3.0	.....	.....	1	Tr	2	Tr	Tr	.....	1	.....

dikes cut across Grenville gneiss and are associated with a granite mass similar in appearance to the Lansdowne granite.

In Table VI Na, K, Ca, Al, and Mg have been reported, in addition to the minor constituents previously sought. The intensities of

TABLE VI

THE MINOR CONSTITUENTS OF SOME PEGMATITE MINERALS

Specimen	Intensity in the Arc Spectrum													
	Na	K	Ca	Al	Mg	Ba	Sr	Mn	B	Cr	V	Sn	Ag	Pb
Smoky quartz	....	....	....	....	1	....	....	....	....	....	....	....	2	....
Peristerite	4	1	3	4	....	....	....	....	1	....	....	....	0.5	0.5
Perthite (1)	8	8	1	4	3	....	....	2	1	1	....	....	1	....
Perthite (3)	6	8	....	4	1	....	....	....	1	....	....	0.5	0.5	0.5
Biotite	1	8	2	4	10	....	....	2	1	5	2	....	....	0.5
Tourmaline	3	....	4	2	6	....	....	2	4	....	0.5	....	....	....

the persistent lines of these elements have not been correlated with the percentage composition, but the figures are still of relative value. The apparent absence of one of these elements cannot be accurately interpreted. For Ca it probably means less than 0.1 per cent and for Mg less than 0.001 per cent.

The most outstanding feature of these minerals is the absence of barium and strontium, and the relatively high concentration of chromium in the specimen of biotite mica. Silver occurs in four specimens and is most abundant in quartz.

THE MINOR CONSTITUENTS OF SEVERAL GRANITES

The minor constituents of fourteen specimens have been listed together in Table VII for purposes of comparison. The majority of the minor constituents are common to all specimens, and the variation of the percentages within a rock suite is somewhat erratic. The presence of silver in a determinable quantity in Lansdowne granite sets off this granite effectively from the others and suggests a comparison with No. 12. Such a comparison shows that the similarity is confined to silver.

CONCLUSIONS

The very common occurrence of Mn, Ba, and Sr in igneous rocks long has been recognized. Manganese occurs in the composition of several ferromagnesian minerals, including some of the amphiboles and some varieties of epidote; and the finding of this element in a magnetic fraction of a granite points to a similar association in the rocks studied.

Barium is known to be a component of the feldspar mineral celsian, and crystals containing several different proportions of orthoclase and celsian have been found. But the existence of a continuous isomorphous series has not yet been fully established. From these facts it may be concluded with a considerable degree of probability that the presence of barium in the light feldspar fractions of granite is due to the replacement of potassium by barium.

The possibility of finding a strontium feldspar has been recognized, and the artificial equivalent has been prepared. Although no corresponding mineral has been found, a complete series of solid solutions with anorthite has been indicated. Since barium and strontium parallel one another so closely, however, in the determinations recorded above, and since potassium and strontium have similar atomic radii, strontium may possibly replace potassium in these feldspars.[6]

[6] P. Eskola, "Silicates of Strontium and Barium," *Amer. Jour. Sci.*, Vol. IV (1922), p. 367.

TABLE VII

THE MINOR CONSTITUENTS OF FOURTEEN GRANITE SPECIMENS AND THEIR INTENSITY IN THE ARC SPECTRUM

No.	Ba	Sr	Mn	B	Cr	V	Sn	Pb	Ag	Co
1	3	3	0.5	0.5	.....	0.1	.....	.....	1	.....
2	0.5	0.5	0.5	0.5	Tr	Tr	.....	.....	1	.....
3	2	3	2	0.5	Tr	0.5	Tr	Tr	0.5	1
4	2	2	0.2	0.5	.....	0.5	.....	.....	1	.....
5	1	1	3	1	1	2	.....	.....	.....	.....
6	5	5	3	1	2	2	.....	1	.....	.....
7	5	5	2	0.5	1	1	.....	1	.....	.....
8	5	5	3	Tr	1	1	Tr	0.5	.....	.....
9	3	4	3	0.1	1	1	.....	0.2	.....	.....
10	Tr	2	3	Tr	1	1	Tr	0.5	.....	.....
11	4	4	3	0.2	0.5	2	.....	1	.....	.....
12	3	4	2	.....	0.5	1	0.2	1	1	.....
13	3	1	2	.....	.....	.....	.....	0.5	.....	.....
14	2	3	2	Tr	0.5	1	0.5	1	.....	.....

The location from which these specimens have come and the age which has been assigned to them is given below:

No.	Location	Age
1	Lansdowne granite No. 1	Middle or late pre-Cambrian
2	Lansdowne granite No. 6	
3	Lansdowne granite No. 7	
4	Lansdowne granite No. 8	
5	Barryfield Hill, Kingston, Ontario	Middle or late pre-Cambrian
6	Knight Township, District of Timiskaming, Northern Ontario	Algoman
7	Fitzgerald, Alberta	pre-Cambrian (undifferentiated)
8	Dana Township	Killarney
9	Pardo Township	
10	Pardo Township	
11	Pardo Township, District of Sudbury, Northern Ontario	
12	Bear's Pass, Rainy Lake	Algoman
13	Elizabeth Mine, Rainy Lake, District of Patricia, Northern Ontario	
14	Sherbrooke, Quebec	Devonian

Boron is not usually determined in chemical analyses of rocks, but the universal association of tourmaline with acid types has been recognized. The spectrographic determinations of boron are in agreement with this fact.

Chromium and vanadium are generally associated with basic rocks. A reason for this may be that these elements replace constituents of some common ferromagnesian mineral. This is suggested by the concentration of chromium and vanadium in the heavy magnetic fraction of the granite, and the occurrence of these elements in biotite from a pegmatite dike.

In this investigation tin and lead have been concentrated with mixed grains composed of quartz and magnetite, and of feldspar and magnetite. These minerals do not show appreciable tin or lead when tested separately, and the only alternative is to assume that these elements are concentrated at contacts of magnetite with quartz and feldspar.

Lead has been reported in a few igneous rocks, usually in localities where ore deposition has taken place. The determination of lead in eight random granite specimens out of fourteen suggests that it is a common minor constituent in granite and that its occurrence may be related to the breakdown of radioactive minerals.

The occurrence of silver in certain specimens of granite is of some importance. Whether the silver is primary or secondary is not definitely established; but since solutions follow cracks and fissures, epigenetic deposits are generally localized to a certain extent; thus the metallic content decreases away from solution channels. The four samples of Lansdowne granite analyzed represent a strip of rock 100 feet long, and the results indicate that the silver content of this portion of the outcrop is uniform. It may be that percolating solutions have completely penetrated the massive granite and deposited silver uniformly throughout the mass, but the evidence so far gathered favors the primary occurrence of this metal.

If the silver is syngenetic, even in the small quantity indicated (0.001 per cent), a study of the derivatives of the original granite magma and a consideration of structure and other factors known to favor concentration might reveal a deposit of economic importance, in spite of the fact that nothing of this nature has been found

to date. The occurrence of lead-zinc deposits associated with a granite generally considered to belong to the same period of intrusion suggests that processes of concentration were not altogether lacking.

If silver is secondary, it is probable that there is a greater concentration in certain parts of the granite mass than in others, and a study of this distribution might lead to the original source or to a locality sufficiently enriched to be of value. In this connection it should be pointed out that during the separation of the granite into specific-gravity fractions, a concentration of silver was effected in more than one fraction showing approximately 0.01 per cent Ag. This is the equivalent of 2.8 oz. per ton of such concentrate.

THE BURIED TOPOGRAPHY OF NORTH-CENTRAL OHIO AND ITS ORIGIN

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ABSTRACT

Examination of 2783 well records in an area of approximately 4,637 square miles in north-central Ohio reveals that the buried topography is similar to that in the unglaciated area of the same state. The writer believes that the preglacial valleys were considerably deepened in interglacial time, during the Deep stage, preceding the Illinoian, and the drainage much disturbed as the result of a glaciation earlier than the Illinoian. Blocking of the northward-flowing streams by this glacier reversed the drainage and caused extensive ponding of the waters in the valleys of the Teays system.

INTRODUCTION

That the topography beneath the glacial drift in the plateau region of northern Ohio is similar to that of the unglaciated portion of the same physiographic province to the south and southeast has been believed for a long time by Leverett[1] and other geologists. No attempt, however, has been made to map the surface. Coffey[2] believes that nearly all the deep valleys in the northeast section of the state, and other sections as well, are of interglacial or postglacial rather than preglacial origin. Wilber Stout,[3] State Geologist of Ohio, agrees, in general, with Coffey. The writer believes that the preglacial valleys were deepened considerably in interglacial time and the drainage much disturbed as the result of a glaciation earlier than the Illinoian.

This article is based on 2783 well records from the files of the Ohio Fuel and Gas Company, the East Ohio Gas Company, the Kemrow Company, and on field work over a period of years. The area, 4,637 miles in extent, lies within a broad, northeast-southwest trending belt of oil and gas wells. It includes Lorain, Cuyahoga, Medina, Summit, Ashland, Holmes, Stark, and part of Tuscarawas and

[1] Frank Leverett, "Glacial Formations and Drainage Features of the Erie and Ohio Basins," *U.S. Geol. Survey Mono. 41* (1902).

[2] George N. Coffey, "Preglacial, Interglacial and Postglacial Changes of Drainage in Northeastern Ohio with Special Reference to the Upper Muskingum Basin," *Ohio Jour. Sci.*, Vol. XXX (November, 1930), pp. 373–84.

[3] Personal communication.

Portage counties. The thickness of the glacial drift, that is, the distance to the bedrock, was recorded and the elevations above sea level

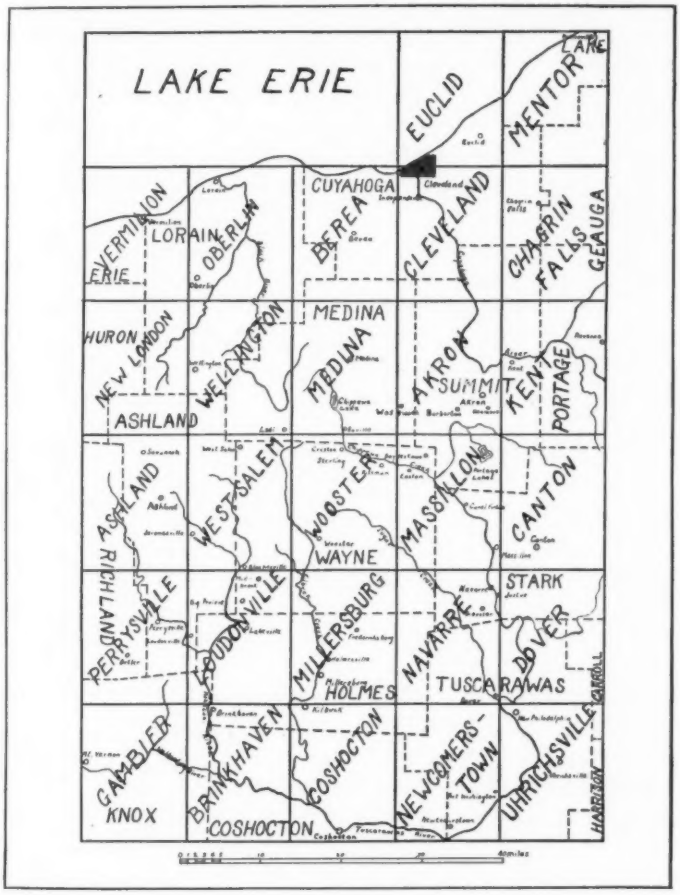

FIG. 1.—Map of the area

computed. From the data, it is possible to obtain the direction of slope and a fairly accurate picture of the topography in preglacial and interglacial time.

PRESENT DRAINAGE AND TOPOGRAPHY

The area discussed in this article lies within the Appalachian plateau and is underlain, for the most part, by the Waverly sandstones and shales. The easterly dipping Pottsville and Allegheny formations cover the eastern portions of Summit and Wayne counties and a large part of Holmes and Stark counties. Outliers of these formations cap the hilltops in Medina, Summit, Wayne, and Holmes counties. In the Lake Plains province in northern Lorain and Cuyahoga counties, and along the Cuyahoga River, the Devonian shales underlie the surface.

The present topography is, for the most part, controlled by glacial drift—rolling in the Lake Plains to the north, and more hilly in the Appalachian plateau to the south. The contrast between hills and valleys becomes greater toward the unglaciated region to the south in Holmes and Tuscarawas counties, where an east-west divide existed in preglacial time, separating the north and south drainage.

In the majority of cases the buried valleys were so deep that the glacial deposits were insufficient in quantity entirely to fill them. This is especially true in the southern part of the area in Holmes, Wayne, Ashland, Richland, and Tuscarawas counties. The larger streams owe their present courses, to a great extent, to the deep sags which, after glaciation, remained on the sites of the old valleys. These depressions, in some cases, offered escape for the waters from the waning Wisconsin ice sheet and were also the sites of glacial lakes. In some of these valleys in the hilly portion of Holmes, Ashland, and Richland counties, the ice sheet did not melt back with a definite front but stagnated in the valleys.[4] The great blocks of stagnant ice left depressions which once were occupied by lakes, as some still are. These valleys measure from $\frac{3}{8}$ mile to more than 2 miles across the top. Although the buried valleys are comparatively narrow at the bottom, the partial drift-filling makes them broad and flat bottomed or rolling, with morainal mounds here and there. The postglacial streams are often misfits—very small in comparison to the broad valleys they occupy. In the southern quadrangles, such

[4] George White, "An Area of Glacial Stagnation in Ohio," *Jour. Geol.*, Vol. XI (1932), pp. 238–58.

as the Perrysville and Millersburg, where the ice was thin, glacial deposition did not change the relief as much as in the more heavily glaciated sections to the north.

THICKNESS OF THE DRIFT

Well records of fourteen quadrangles show that the average thicknesses of the drift over the buried uplands range between 37 and 67 feet. Nine quadrangles show thicknesses ranging from 47 to 57 feet, two above 57 feet, and three below 47 feet. The drift is thinnest over the uplands along Lake Erie where bedrock outcrops appear in many places. The average thickness over the buried uplands in the entire region is 51 feet. The thickness of the glacial deposits in the buried valleys averages from 155 feet (Wellington quadrangle) to 380 feet (Cleveland quadrangle). Maximum thicknesses, in feet, for the fourteen quadrangles range from 192 to 763 feet. Thicknesses of 300 feet and over are common throughout the area. The average thickness of the drift for all buried valleys in the region is about 205 feet. The thickness of the glacial deposits, over all, taking an average for buried valleys and uplands combined, is 95.7 feet. The northernmost quadrangles, the Oberlin and Berea, have the least thickness, 54 and 43 feet respectively, whereas the area farther south, represented by the Medina, Akron, Ashland, West Salem, Wooster, Massillon, Canton, Perrysville, Loudonville, and Millersburg quadrangles have thicknesses of 85, 111, 90, 81, 80, 154, 97, 88, 90, and 94 feet respectively. Where the greater thicknesses occur, either deeper buried valleys or belts of thicker moraine are present. The greatest thickness in the entire area and possibly in the state of Ohio, 763 feet, is located south of Cleveland in Newburg Township, about 2 miles directly east of the town of Independence. Here, where a north-south buried valley marks the course of the preglacial and interglacial Cuyahoga River, bedrock is 13 feet below sea level and 586 feet below the present level of Lake Erie. Other thicknesses in this valley are 605, 560, 519, and 500 feet and many more greater than 400 feet.

THE BURIED VALLEYS

The altitude of the floors of the buried valleys varies from 13 feet below sea level to 900 feet or more above. In the Cleveland and

Euclid quadrangles the floor of the old Cuyahoga varies from 13 feet below to 400 feet above tide. Elevations above sea level of 78, 80, 135, 145, 155, 161, 176, 196, and 200 feet and above, mark the course of the old Cuyahoga River. These points range from 273 to 586 feet below the present level of Lake Erie. The old Cuyahoga, throughout its buried course within the limits of the Cleveland quadrangle, is well below the present level of Lake Erie and at only a few other points in the area are the buried valleys below the level of the lake. With the exception of the old Cuyahoga, the floors of the buried valleys in the area stand at an altitude which varies from 511 to 900 feet or more above tide, the majority extending from 600 to 800 feet above that datum plane.

A question which naturally arises in connection with any study of the buried valleys is the effect of glaciation. It is known that in other plateau regions where glaciation took place valleys oriented with the direction of ice movement were deepened, i.e., the Finger Lakes region of New York. Repeated glacial erosion might account for the great depth of the channel of the old Cuyahoga. It has a north-south trend, in line with the movement of the ice. The push of the glacier from the Lake Erie depression against the scarp and upon the plateau to the south would produce great scour and erosion.

The gradient of the buried valleys as compared with that of valleys now existing gives some interesting information. The buried valley of the old Mohican River, shown on the Perrysville and Loudonville quadrangles, has a gradient of about 14.7 feet per mile, whereas at present for the same distance it is 6.5 feet per mile. The buried valley in which flows the Killbuck (West Salem and Wooster quadrangles) has a fall of 21 feet per mile, but the present floor slopes only 4 feet per mile. The buried valley of Chippewa Lake in Medina County shows a drop of 144 feet in 7 miles, whereas at present it shows a gradient of but 9 feet in the same distance. The buried channel of the old Cuyahoga has a fall of about 28 feet per mile in the vicinity of Independence, whereas at present, for the same distance it is 4 feet per mile. Not all the buried valleys have high gradients; Jerome Fork of the Mohican River (Ashland and West Salem quadrangles) and Killbuck Creek (Wooster and Millersburg quadrangles), flow above buried valleys which have a fall considerably less than the present fall.

Just what effect glacial erosion had in determining the gradients of the buried valleys cannot be established. The evidence points to gradients on the buried surface steeper than in the present drift-floored valleys. Gradients of the buried valleys are equal to, if not greater than, those of equal size in the unglaciated section of Ohio. The slope of the valley walls is comparable with that of those in the unglaciated region immediately to the south and southeast. The buried valleys of northern Ohio are not so steep walled as present-day valleys in the higher plateau area in southeastern Ohio and West Virginia. A possible exception may be the gorge of the old Cuyahoga.

TABLE I

APPROXIMATE AVERAGE AND MAXIMUM RELIEF OF THE PRESENT SURFACE

Quadrangle	Average Relief (in Feet)	Maximum Relief (in Feet)
Oberlin	33	277
Berea	132	687
Cleveland	445	707
Wellington	119	420
Medina	240	442
Akron	395	620
Ashland	270	500
West Salem	250	400
Wooster	205	356
Massillon	230	340
Canton	110	300
Perrysville	337	526
Loudonville	282	477
Millersburg	400	553

RELIEF OF THE BURIED TOPOGRAPHY

In an attempt to visualize the buried topography, it is necessary that the relief be known and compared with that in the unglaciated region in Ohio, south of the glacial boundary. It is also of interest to note how the buried topography compares with the present surface in the same area. Three tables are here presented showing the average and maximum relief of the present surface of the buried topography of the area under discussion, and the relief of sections in the unglaciated region in southeastern Ohio.

A glance at the figures indicates that with the exception of the rugged topography of the Wheeling, New Martinsville, and St. Clairsville quadrangles in the higher plateau area of West Virginia and extreme eastern Ohio, the relief is about the same as that of the buried topography. The high average relief of the Cleveland, Akron, and Massillon quadrangles is explained by the great depth of the

TABLE II

APPROXIMATE AVERAGE AND MAXIMUM RELIEF OF THE BURIED TOPOGRAPHY

Quadrangle	Average Relief	Maximum Relief (in Feet)
Oberlin	No deep buried valleys	171
Berea	190 ft. in lake plains –420 ft. in plateau	651
Cleveland	800–850	1,223
Wellington	350	497
Medina	350	621
Akron	626	794
Ashland	350	777
West Salem	300	492
Wooster	380	535
Massillon	450	552
Canton	200	287
Perrysville	350	581
Loudonville	350	584
Millersburg	450	557

old Cuyahoga channel. It is obvious that the glacial deposits cover a mature topography as rugged as that in the unglaciated plateau region of southeastern Ohio.

BURIED PENEPLAINS

In view of the fact that the buried topography is similar to that in the unglaciated portion of Ohio, one would anticipate that the same erosion surfaces are present beneath the drift. The elevation of the buried uplands can be determined from the numerous well records throughout the area. Over the plateau section of the region, the average altitude of the buried upland is about 1,100 feet

above sea level. It is somewhat higher in a few quadrangles (Loudonville, Millersburg, Perrysville) which lie to the south near a major divide, much of which stands over 1,200 feet above tide. Many points are well above the general level, some being 1,300 feet or more. The general upland surface, as indicated by an altitude of about 1,100 feet, is identical with the Harrisburg level, which extends over the unglaciated portion of Ohio and the Allegheny plateau. This peneplain slopes gently toward the streams and usually merges, without abrupt change, into the Worthington surface near the valleys. In southeastern Ohio the two surfaces are distinct, the Harrisburg peneplain standing at an average altitude of about 1,200 feet, and the Worthington at an average elevation of about 1,000 feet, or as low as 900 feet along the Ohio River in the southeastern part of the state. In the plateau section of the area, the shoulders which stood above the valleys and from the uplands, now buried, in the vicinity of the streams, have an altitude varying from 900 to 1,000 feet, an average elevation which corresponds with the altitude of the Worthington surface of southeastern Ohio.[5] At places

TABLE III

APPROXIMATE AVERAGE AND MAXIMUM RELIEF IN THE UNGLACIATED REGION OF OHIO

Quadrangle	Average Relief (in Feet)	Maximum Relief (in Feet)
Coshocton	372	506
Zaleski	340	430
Laurelville	365	520
Uhrichsville	368	469
Dover	290	380
Cambridge	345	480
Antrim	327	468
St. Clairsville	540	702
Wheeling	722	866
New Martinsville	670	800
Caldwell	388	544
Woodsfield	443	589
Cumberland	290	466
Conesville	337	405

[5] Karl Ver Steeg, "Erosion Surfaces of Eastern Ohio," *Pan-Amer. Geologist*, Vol. LV (March-April, 1931).

where the glacial drift is thin or where the rock crops out, the beveled shoulders, standing well above the present valley bottoms, are visible.

The Parker strath, which corresponds with the Teays Valley level of West Virginia and southern Ohio, may be present in the buried valleys, but no definite evidence for it exists. There are many localities where occur what might be interpreted as remnants of valley flats or benches: in the buried valley south of Wooster, in the one south of Sterling where flows Chippewa Creek, and in the broad, buried valley at the conjunction of Jerome and Muddy Forks near Funk (West Salem quadrangle). It would seem that during the Deep stage which followed the Parker strath stage, the valley flats representing the later period were removed by erosion. Glacial erosion may likewise have aided in the removal of this surface from the valleys. Beneath the Lake Plains, in the northern portion of Lorain and Cuyahoga counties, the elevation of the buried upland varies from 600 feet or less near Lake Erie, rising to above 800 feet near the plateau. This surface was scoured and doubtless considerably eroded by the ice but probably represents an old erosion surface. The glacial drift which covers it is somewhat thinner than that which buries the plateau upland farther south, averaging about 37–40 feet, whereas on the plateau an average of 50 feet over the uplands is more common. This difference in the thickness of the drift might be explained by the fact that the glacier eroded more here than farther south, where the ice pushed its way southward to higher elevations, stagnated, melted, and deposited its load. Could the buried surface beneath the Lake Plains, developed on the weaker Devonian shales, be the equivalent of the Parker strath or the Teays Valley in southeastern and southern Ohio? Professor Fenneman, of the University of Cincinnati, in a recent communication to the writer, mentions the existence of an erosion surface under the Maumee and Scioto basins in western Ohio. He remarks, "I have assumed that the shale lowlands under the Maumee and Scioto basins represent a well-advanced partial cycle which is later than the prevalent limestone uplands in western Ohio and Indiana." The writer believes that the buried surface developed on the shales beneath the plain south of Lake Erie, standing at an altitude of about 600–

800 feet above sea level, represents the same cycle of erosion as that on the buried lowlands beneath the Scioto and Maumee basins, and is the equivalent of the Parker strath or Teays Valley level.

GEOLOGICAL HISTORY

To understand the sequence of events in the glaciated area of Ohio, it is necessary to study the geological history of the unglaciated section. The glacial drift covers a topography similar to that in the unglaciated region and its history is, with the exception of glaciation, the same. Wilber Stout, director of the Ohio State Geological Survey, has supplied the writer with sufficient data to give the following picture of the geological history of the unglaciated portion of the state.

In late Tertiary time the land surface, now at about 1,000–1,100 feet, was beveled by the Worthington peneplain. Uplift took place and the streams cut down, ultimately forming the Parker strath. This erosion surface was developed in the river valleys of Ohio at an altitude of about 600 feet and is identical with the strath cut by the Teays system of rivers in West Virginia and southern Ohio. The low relief of a fairly mature river system developed a decided strath stage, the Teays itself having a gradient of only 8–10 inches per mile. The old Teays River, a large stream of Parker strath time, flowed northward through the broad valley now occupied by the Scioto River. At Chillicothe this valley disappears beneath the glacial drift. Here the old floor of the Teays is slightly above the present drainage. From Chillicothe northward the course of the river is lost, without evidence as to whether it continued to the north or northwest. It did not pass through any of the valleys in the area discussed in this article. Its most probable course was to the north through the broad lowland now occupied by the tributaries of the Scioto River in western Ohio. The Teays River had its source in the mountains of western North Carolina and from there it flowed through the valleys now occupied by the New and Kanawha rivers, through Virginia and West Virginia, to a point near St. Albans, where it turned westward to flow through the deserted Teays Valley. Near Huntington it entered the present Ohio Valley which it followed most of the way to a point near Wheelersburg. Here it flowed

northward to Waverly where it entered the present Scioto Valley. Stout and Schaff[6] have shown that the Teays River extended eastward over the Piedmont plateau, probably as far as the Fall Line. They have found mica (Minford) silts along the valleys once occupied by the streams of the Teays system, the source of which must be the igneous and metamorphic rocks of the Piedmont plateau. It is believed that the Teays (Parker strath) cycle of erosion lasted until the close of the Tertiary, and the level of the streams which were occupying the courses they had throughout the Tertiary was reduced to about 660 feet above sea level, which is the approximate altitude of the Parker strath or Teays bench.

The second event was the coming of one of the early glaciers, probably Kansan or pre-Kansan, which changed the ancient Tertiary drainage system. The ice dammed the lower courses of the Teays River and its tributaries, ponding the waters and giving rise to a flood or slack water stage. Heavy silting of fine sands occurred, with an upper coating of Minford silt, laid down entirely across the valleys of the Teays system. This silt is not a flood-plain deposit for it is not mixed with sand and gravel. Field evidence indicates the presence of silts as much as 860 feet above tide, with water depth much above that altitude. The silt is extremely fine grained, made up of about 50 per cent of sericite scales, is without free silica, and has false plasticity. This material is believed to have come from the Piedmont crystallines. One of two things must be assumed: ponding caused by an early drift sheet or by a rise of the land, forming a barrier to the north. No evidence now known supports a rise of the land to the north. If the land did rise, there must have been subsidence since that time. Hence, damming by an earlier drift sheet, Kansan or pre-Kansan, is supposed. How far south the early ice sheet advanced in Ohio is a question which cannot be answered at present. We can state that there is no outwash from any glacier in the old Teays valleys.

The third event involves the development of an entirely new system of drainage. As a result of the ponding of the water in the lower Teays system, the general direction of the master streams in

[6] W. Stout and D. Schaff, "Minford Silts of Southern Ohio," *Bull. Geol. Soc. Amer.*, Vol. XLII (1931), pp. 663–72.

southern Ohio was reversed, flowing westward instead of northward as before the advent of the ice sheet. This is known as the Deep stage drainage and bears little resemblance to the Teays. It cut across many Teays valleys and shows numerous reversals. The master stream gathered waters north and east of Newark, flowed past Buckeye Lake, Circleville, Chillicothe and Portsmouth, and westward to Cincinnati. At Portsmouth it was joined by the Deep stage Ohio River, the headwaters of which are not determined. This stream cut down rapidly along the lower reaches, at Portsmouth for example, 200 feet below the old Teays Valley. Strange to say, it cut through highland areas in many places meaning that the flooding was deep and the streams cut across in an unusual manner. These strange freaks of degradation can apparently be explained only by extreme flooding and not piracy.

The new drainage reached early maturity or late youth in the erosion cycle. The region was well dissected throughout. Many of the streams developed entirely new valleys and it took a long time to accomplish the dissection; for example, the present Ohio River was the result. The work was carried on with sufficient rapidity so that a low gradient was not developed on the tributaries.

But what does reversal of drainage and the mature dissection, with the cutting of stream valleys, 200 feet below the Teays valley, mean? Does it indicate a rise of land or a nearer way to the ocean? The Teays River may have had a long way northward and eastward to the ocean, while the newer system, the Deep stage Ohio, cut westward to the gulf (Tertiary embayment). This shorter route may account for the deeper dissection. The depth of the buried valleys in the glaciated region, such as the old Cuyahoga, seems to favor higher land, possibly rising during the Deep stage, and subsidence later with the advent of the later ice sheets. The Deep stage lasted from the flood stage of the Teays to the advent of the Illinoian glacier.

The fourth event was the interruption of the Deep stage by the Illinoian glaciation, with the filling in of the valleys in the glaciated areas and outwash filling beyond the drift borders. Away from, or beyond the border of the glacier, new streams were not developed and the Deep stage valleys were undergoing aggradation and were not being excavated. Apparently not much work was accomplished

in the way of clearing out the Illinoian drift and outwash. In places most of the outwash appears to be Wisconsin drift. Hence there may have been more clearance than supposed. The Deep stage valleys are filled with the gravels of the later period. No Illinoian or Wisconsin outwash is present in the Teays Valley. The Scioto Valley at Waverly is filled with more than 100 feet of outwash, but it did not reach to the level of the Teays Valley there. The Wisconsin epoch of glaciation was a repetition of the Illinoian, with the exception of far more outwash and more local stream modifications near the border, such as the Black Hand gorge near Newark, the Mohican River, and Jonathan Creek gorges.

The closing event has been the development of the drainage on the drift, which in Ohio is about 70 per cent unmodified, or practically as the Illinoian and Wisconsin glaciers left it. In the Deep stage, in valleys like the Scioto at Waverly, all that has happened has been the cutting out of the gravel fill to a depth of 30–40 feet, an altitude which marks the upper level of the gravel terrace, but still stands well below the Teays level. All that has happened in the Scioto Valley at Waverly or south of Chillicothe, since Illinoian time, has been the filling of the valley to a depth of 140 feet and then the eroding of it to a depth of 40 feet. The amount of erosion done from Teays through Deep stage time is very large, as the present Ohio valley is cut more than 200 feet below the old Teays River Valley. Some idea of the age of these stages could be obtained by a study of the amount of work done in carving the valleys. The amount of erosion accomplished since Wisconsin time is very small. The length of time required during the Deep stage to carve the Ohio Valley, or a valley like that east of Newark, cut through the highlands at a depth of 600 feet, must be quite large. The Teays drainage represents only a comparatively small amount of work, as it is simply a deepening of the old channels on the Worthington surface. If the amount of work done during each period of time is compared, the Deep stage far exceeds the other. But the Teays erosion represents far more work than has been done by the present streams since the Ice age.

PREGLACIAL DRAINAGE

The existence of a major divide extending in a northwesterly direction from a point near Port Washington on the Tuscarawas River,

crossing Killbuck Creek south of Millersburg, near the town of Killbuck, where there is a col, has been pointed out by the writer in an earlier paper.[7] Farther west another deep, narrow col appears, where the divide crosses the Mohican River. From this point the divide continues westward, merging into the lowlands of eastern Ohio. From this high divide the watershed, in general, slopes northward and the evidence is strong that the preglacial drainage was toward the north and northwest (Fig. 2). It is probable that the preglacial drainage existed in broad, open valleys at a higher level than at present. Coffey[8] remarks:

> Nearly all of the country below 1,100 feet in elevation is in the important valleys or on the immediately adjoining slopes. The so nearly uniform height of the uplands is very strong evidence that the country was reduced to a peneplain with a surface sloping gently from the higher divides toward the broad valleys. . . . . In other words the western extension of the plateau into Ohio had, before the beginning of the ice-age, been reduced to a peneplain and the fairly stable conditions then existing were disturbed by the first advance of the ice.

Coffey does not indicate on what peneplain the streams existed just before the advent of the first ice sheet. It would seem that he is speaking of the Harrisburg surface at about 1,100 feet, a peneplain which is represented by the hilltops and divides in Ohio at about 1,100 to 1,200 feet. The writer believes that the streams, just before the coming of the first ice sheet, were occupying broad, open valleys at a lower level, represented by the Parker strath or Teays stage. The narrow, gorgelike character of the buried valleys seems to indicate that the Parker strath was largely removed by stream erosion during the Deep stage and by subsequent glacial erosion. When the ice appeared, it is probable that Ohio, including the glaciated area, was in the Parker strath stage. The streams which were established on the Worthington peneplain, represented by the uplands along the valleys at about 1,000 feet, were rejuvenated by uplift and had reached the mature stage, as indicated by the Parker strath, when the ice made its first appearance.

Conotton and Stillwater creeks, rising in northwestern Belmont and eastern Harrison counties flow northwestward into Tuscarawas River. They represent streams the direction and location of which, no doubt, are the same as in preglacial time. Stillwater Creek flowed

[7] *Op. cit.*, p. 96.

[8] *Op. cit.*, pp. 374–76.

along the present channel of Tuscarawas River and Sugar Creek as far as Brewster, and the old Conotton along the present course of the

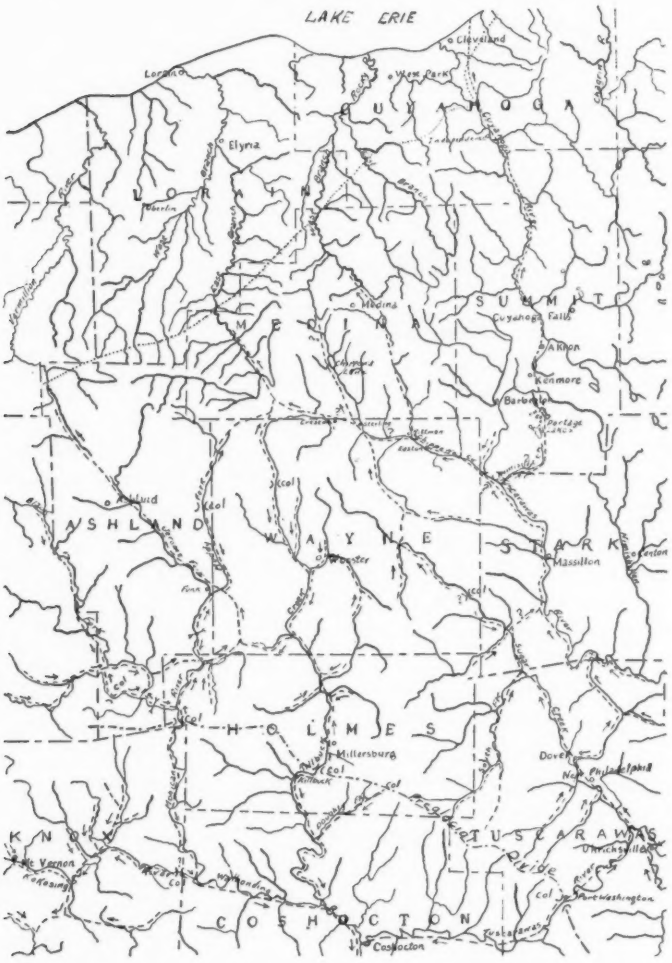

FIG. 2.—Preglacial drainage indicated by the dashed lines. Approximate boundary between the Lake Plains and the plateau indicated by the dotted lines.

Tuscarawas as far as Navarre. The preglacial Stillwater probably turned at Justus and joined the old Conotton, flowing northward to Massillon. The preglacial Tuscarawas may have been a part of the old Cuyahoga, for a buried channel exists along the site of Nimisila Creek northeast of Canal Fulton. Another possible route for the waters of the old Tuscarawas was in a northwesterly direction in the broad valley northwest of Canal Fulton. It may have flowed through the old valley east of Medina or through the buried valley at Lodi. A large stream occupied the valley at Lodi and another may have flowed northward by way of the depression at Chippewa Lake, although the evidence does not favor this route. Farther south, the streams which occupied the broad valleys at Wooster and Millersburg joined those coming from the west and flowed northwestward through the wide valley east of Ashland.[9] Because of the complexity of the changes wrought as a result of glaciation, each successive advance of the ice causing further changes in the drainage, resulting in rejuvenation of the forces of erosion and the carving out of deeper valleys, the location and direction of the preglacial streams can only be approximate. The direction of the preglacial streams, as one would expect, was from the major divide in a northwesterly direction toward the western plains, instead of the present courses which are toward the high hills to the south and southeast.

INTERGLACIAL DRAINAGE

The contour map (Fig. 3), based on data obtained from nearly 2,800 oil well records, water well records, and rock outcrops represents with a fair degree of accuracy the general contour of the buried land surface. This topography was developed during the Deep stage, following an early epoch of glaciation (Kansan or pre-Kansan), which was responsible for great changes in the drainage. The topography of the Parker strath or Teays stage was mature, the broad open valleys standing well below the Worthington upland. The ice, as it advanced over the plateau, blocked the streams which were flowing in a north and northwesterly direction and reversed the drainage. A comparison of the two maps (Figs. 2 and 3), illustrates

[9] Ver Steeg, "Drainage Changes in the Vicinity of Loudonville, Ohio," *Ohio Jour. Sci.*, Vol. XXXI (September, 1931), pp. 368–76.

the changes that took place. The drainage was ponded, doubtless forming lakes in front of the ice sheet, the water flowing over the

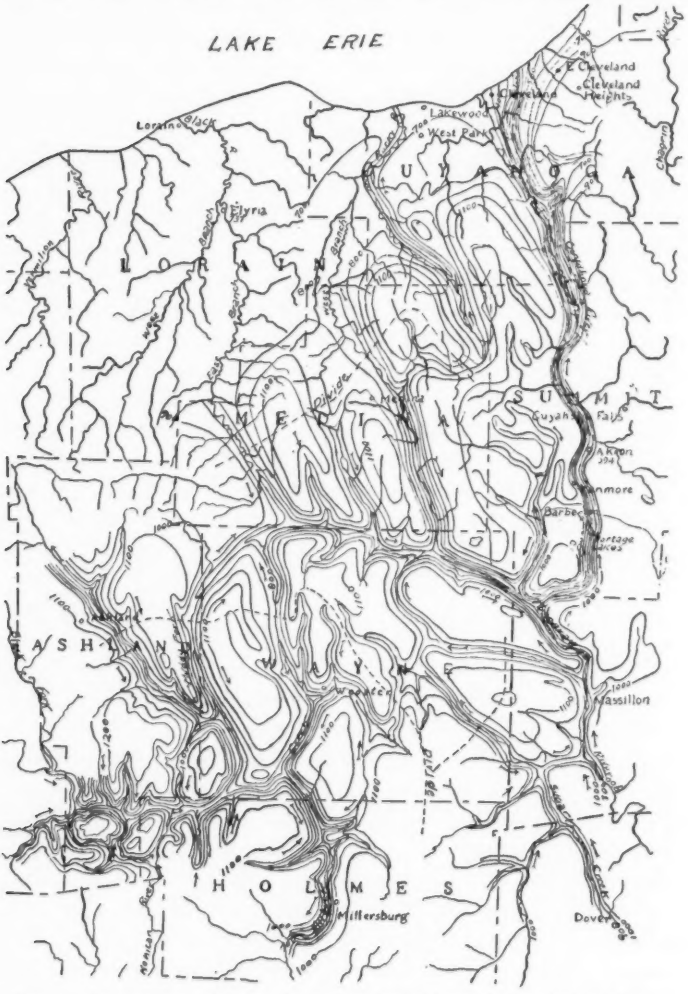

FIG. 3.—Contour map showing the surface buried beneath the glacial drift. Contour interval 100 feet.

divides to the south. No doubt the old Tuscarawas was ponded, and the waters may have flowed southward over the divide near Port Washington. Apparently the reversal of drainage in the old Tuscarawas and old Cuyahoga Valley was only temporary, for the bedrock slope of the buried valley of this stream is to the north. The ponded waters of the blocked streams had three possible exits to the south, one over the preglacial col and by way of the valley near the town of Killbuck, another over the col at Port Washington, and perhaps one more over the divide by way of the Mohican River, although this valley is considered later in age. How far south the ice extended over the plateau cannot be determined. It is probable that the ice eroded and otherwise modified the valleys of the Parker stage. No doubt, glacial till and glaciofluvial material filled them to a greater or lesser degree. After the ice withdrew, the Teays valleys were left, filled with drift, and the drainage lines obliterated or disarranged. During the long interglacial epoch, the Deep stage, the Parker strath valleys were excavated and deepened and new valleys were cut where the streams did not follow the old channels. The topography as illustrated by the map (Fig. 3) was developed during this stage. Two divides separated the drainage into three distinct basins during the Deep stage: one to the north, the streams flowing to the plains and into the Erie basin; one to the south, the streams draining southward by way of the present Killbuck; and another, the largest of the three, occupying a central position in the area. The streams of the latter drained eastward and joined the waters of the old Tuscarawas to make the old Cuyahoga, which flowed in a deep gorge into the stream or lake which at that time occupied the Erie basin. The buried floor of Conotton and Stillwater creeks and the Tuscarawas River slopes to the north indicating northward drainage during the Deep stage. The withdrawal of the ice at the close of the first glacial epoch opened a lower exit for the waters to the north by way of the old Cuyahoga, and the outlet at Port Washington was abandoned. The Port Washington outlet may have been temporary, the water pouring over the col from a ponded lake which existed only as long as the ice formed a barrier to the north. When this obstacle was removed the waters took the lower outlet to the north by way of the old Cuyahoga.

During the Illinoian epoch the ice invaded the valleys of the Deep stage and may have deepened and changed them to some extent. Scranton and Lamb,[10] in an article discussing the drainage changes in the region immediately to the west, attribute some of the peculiarities in the buried valleys to glaciation, and believe "that the deep inner valleys of the various preglacial streams of the region were excavated after the earliest glaciation, but before the Illinoian." A long interglacial epoch followed the Illinoian ice invasion. This period, however, was not long enough to remove the glacial material from the valleys of the Deep stage. The drainage was again disturbed by the Wisconsin glacier, leaving the topography much as it is today.

[10] Robert Scranton and G. F. Lamb, "Ancient Drainage between the Old Cuyahoga and the Old Pittsburgh Rivers," *Ohio Jour. Sci.*, Vol. XXXII (November, 1932), pp. 481–86.

STRATIGRAPHY OF THE OKAW IN SOUTHWESTERN ILLINOIS

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ABSTRACT

The Okaw division of the Chester (late Mississippian) series of southwestern Illinois which heretofore has been considered middle Chester in age, is shown to be separated into two mapable parts by a disconformity. The lower unit, Lower Okaw, is of middle Chester age and the higher portion, Upper Okaw, is of late Chester age. Each of these units is described and correlated on paleontologic, lithologic, and stratigraphic grounds with a definite portion of the standard Chester section of Hardin County, Illinois, and western Kentucky.

INTRODUCTION

Several years ago when the late Professor Stuart Weller initiated his work on Chester stratigraphy in St. Clair, Monroe, and Randolph counties, Illinois, he designated in print[1] and in manuscript[2] as the Okaw formation, a considerable thickness of Chester strata lying between the Ruma (Cypress) formation below and the Menard limestone above. Somewhat later he designated as the Okaw group the strata of middle Chester age (Cypress, Golconda, Hardinsburg, and Glen Dean formations),[3] suggesting by this publication that he considered the Okaw, as originally defined by him, as being entirely of middle Chester age.

Between the time of Weller's first and last papers referred to previously, another paper using the term "Okaw" to include beds ranging in age from Golconda to Glen Dean made its appearance.[4] In addition, Weller prepared other manuscripts for the Illinois State Geological Survey using the name "Okaw." In none of these writings is there any suggestion that the Okaw may include beds younger than the Glen Dean of the section farther east in the Eastern Interior

[1] "Stratigraphy of the Chester Group in Southwestern Illinois," *Trans. Ill. State Acad. Sci.*, Vol. VI (1913), p. 127; "Mississippian Brachiopoda," *Ill. State Geol. Surv., Mono.* I (1914), pp. 27–28.

[2] "Report on the Geology of Parts of St. Clair, Monroe and Randolph Counties, Illinois." Manuscript and maps made available for the writer through the courtesy of the Ill. State Geol. Surv.

[3] "The Chester Series in Illinois," *Jour. Geol.*, Vol. XXVIII (1920), p. 285.

[4] E. O. Ulrich, "Mississippian Formations in Western Kentucky," *Ky. Geol. Surv.* (1918), pp. 56, 57, 195, 223, and others; Plate 2.

Basin, all of them indicating the absence of strata equivalent to the Tar Springs, Vienna, and Waltersburg formations of the eastern area. The purpose of this article is to show that the Okaw consists of two well-defined portions separated by a disconformity. Weller[5] noted this erosion surface but did not recognize a late Chester age for the Okaw beds above it.

During the summers of 1932 and 1933 the writer examined the Okaw and identified in it five and possibly six of the formations of the standard Chester section. These formations have been grouped into two well-defined mapable units, one of middle Chester and one of late Chester age, and each correlated with a definite portion of the Chester farther east in the Eastern Interior Basin. Although the name Okaw has been used with different meanings, it has been retained and the two divisions designated as Lower and Upper Okaw. The writer believes that this is justified because the name is well known and because these stratigraphic units occur in only a limited area.

The following correlation chart (Fig. 1) shows the relations of the Okaw as considered by Weller and the writer to the general Chester section.

<table>
<tr><th colspan="2">Standard Chester Section of Hardin County, Illinois</th><th colspan="2">Weller's Section for Southwestern Illinois</th><th colspan="3">The Writer's Section for Southwestern Illinois</th></tr>
<tr><td rowspan="4">Upper Chester</td><td>Menard</td><td colspan="2">Menard</td><td colspan="3">Menard</td></tr>
<tr><td>Waltersburg</td><td colspan="2" rowspan="3"></td><td rowspan="6">Okaw</td><td rowspan="3">Upper Okaw</td><td>Waltersburg member</td></tr>
<tr><td>Vienna</td><td>Vienna Member</td></tr>
<tr><td>Tar Springs</td><td>Tar Springs Member</td></tr>
<tr><td rowspan="4">Middle Chester</td><td>Glen Dean</td><td rowspan="3">Okaw Formation</td><td>Upper Okaw</td><td rowspan="3">Lower Okaw</td><td>Glen Dean Member</td></tr>
<tr><td>Hardinsburg</td><td rowspan="2">Lower Okaw</td><td>Hardinsburg Member</td></tr>
<tr><td>Golconda</td><td>Golconda Member</td></tr>
<tr><td>Cypress</td><td colspan="2">Ruma (Cypress)</td><td colspan="3">Cypress (Ruma)</td></tr>
</table>

FIG. 1.—General correlation chart of the southwestern Illinois and standard Chester sections. This chart does not include all of the Upper Chester.

[5] "Report on the Geology of Parts of St. Clair, Monroe and Randolph Counties, Illinois" (Manuscript).

GENERAL FEATURES OF THE OKAW

The Okaw is the thickest Chester unit in this portion of Illinois and includes the most typical of Hall's "Kaskaskia Limestone" and Shumard's "Upper Archimedes Limestone." It consists of alternating limestone and shale beds with sandstone in the upper portion, the entire series attaining a thickness of about 300 feet. The limestones which are variable in lithology and thickness, because of their greater abundance and better exposures, constitute the most conspicuous portions. Some are quite pure, light-gray or bluish in color, and more or less crystalline. Others are more argillaceous with shaly partings. In some localities conspicuous white oölitic beds are present and in other places beds, not conspicuously oölitic, contain scattered oölites. In general the limestones are free from chert although one conspicuous cherty and sandy horizon occurs in the Lower Okaw, and the limestone layers in the middle of the Upper Okaw are often cherty. The shales are as variable in character as the limestones, some being dominantly argillaceous, others highly calcareous, and in the Upper Okaw, associated with the sandstones, some are arenaceous. They are commonly gray, bluish or yellow, with some red and purple beds in a few localities. Sandstones occur in the Upper Okaw, best developed in the lower and upper portions.

The Okaw is overlapped by Pennsylvanian strata in the northern portion of its area of outcrop and dips beneath younger formations toward the southeast. The northernmost exposures occupy small isolated areas surrounded by Pennsylvanian rocks, the result of recent erosion exposing the irregular pre-Pennsylvanian erosion surface of the Mississippian beds. Several of these inliers occur in St. Clair County in both the Waterloo and New Athens quadrangles (Fig. 2). The continuous belt of Okaw begins in the lower portion of Prairie du Long Creek about 2 or 3 miles from its junction with Richland Creek, extends eastward to the east side of Okaw (Kaskaskia) River, and probably a considerable distance northward in the Okaw Valley beneath the alluvium. The continuous belt extends southward to the Mississippi River bluffs, the channel of Okaw River, probably from New Athens or above to its mouth, being in it, although alluvium effectually hides all bedrock along the stream. This belt of outcrop averages between 6 and 7 miles in width

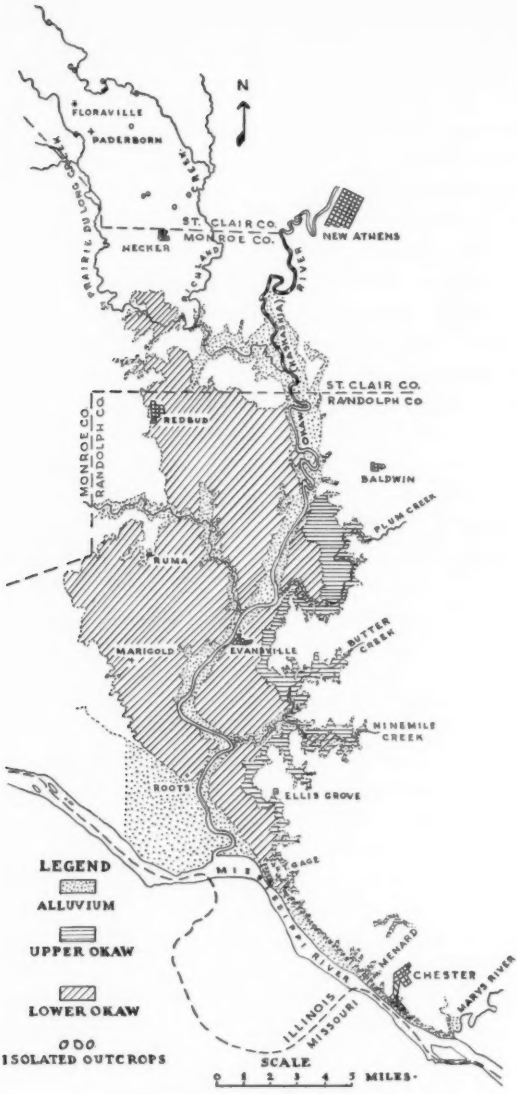

FIG. 2.—Sketch showing Okaw distribution

with a maximum of 10 miles along an east-west line about 2 miles north of Evansville. The Okaw first appears in the Mississippi River bluffs about 3 miles above the Okaw River gap and continues to the mouth of Marys River. Throughout the southern portion of its extent, from about a mile north of Fort Gage, it occupies a narrow strip at the base of the bluff below younger beds, with the exception of one inlier north of Chester.

Throughout much of its area of occurrence the Okaw is covered by varying thicknesses of glacial and alluvial deposits so that good exposures are not abundant. This naturally makes delimitation of the exact boundaries difficult and almost impossible in some localities.

DETAILED FEATURES OF THE OKAW

Lower Okaw.—This portion of the section, because of its greater thickness and approximate coincidence of dip angle and surface slope west of Okaw River, occupies most of the area underlain by the Okaw. The Golconda portion, which rests conformably on the Cypress (Ruma), consists predominantly of limestone with minor amounts of shale as partings or as thin shale beds alternating with limestones. The limestone varies in color from white through gray to some beds which are yellowish. Much of the limestone is crystalline in texture, but in many places the beds are oölitic. One conspicuous white oölitic zone which has been called Marigold oölite by Weller,[6] occurs a little above the middle of the Golconda, from 50 to 60 feet above the base. This member averages around 20 feet in thickness and is well displayed in the upper portions of the valleys which head in the ridge extending south from Marigold. It is also exposed near Roots and at Evansville as well as in other localities in the western portion of the Okaw outcrop belt. The shales of the Golconda are argillaceous and usually bluish gray or yellowish in color. The Golconda division of the Lower Okaw crops out along the western side of the Okaw belt and in several of the isolated occurrences north of the main area of exposure. As nearly as can be determined the Golconda member attains a thickness of 100 feet, more or less.

It is impossible to delimit the Golconda from the higher Glen

[6] *Ibid.*

Dean with any degree of certainty except in one general locality. This is in the area south of Marigold, where the two are separated by a thin horizon of chert and cherty sandstone from 1 to 3 feet thick. The writer believes that this zone represents the northwestern extension of the Hardinsburg which, as a well-defined sandstone, separates the Golconda and Glen Dean formations farther south and east in Illinois. The beds below the sandy zone contain characteristic Golconda fossils, and those above, Glen Dean fossils. Elsewhere this zone is either absent or masked by a covering of surficial material. In localities where the Hardinsburg equivalent is absent the limestones can be differentiated by fossil content, but the line of separation cannot always be ascertained with any degree of exactness.

The Glen Dean member consists of non-oölitic, gray, more or less crystalline limestone with interbedded shale. The most conspicuous portion is a massive, thick-bedded limestone zone, from 37 to 50 feet thick near the top. This is the quarry ledge of the prison quarries at Menard, and extends both south and north from the prison. It is well exposed in the ravines between Menard and Chester and in the south part of Chester, but dips under cover within a short distance southward. North of the Mississippi bluff portion of the outcrop this massive limestone is exposed in many of the smaller stream courses. The strata below the quarry ledge consist of thinner bedded limestones and shales. In places, above the quarry ledge, varying amounts of alternating thin limestones and shales attain a maximum thickness of 15 feet or more. Locally these higher beds are missing and the lowest sandy beds of the Upper Okaw rest upon the more massive limestones. The Glen Dean attains a maximum thickness of about 125 feet, but locally is much thinner.

Upper Okaw.—This portion of the Okaw of late Chester age rests disconformably upon the Lower Okaw. It crops out as a narrow band along the Mississippi bluff from the mouth of Marys River to Ft. Gage and over a limited area along the eastern side of the Okaw belt almost as far north as the latitude of Baldwin. It consists of three more or less distinct units which are correlated with the lower formations of the Upper Chester group. The lower and upper members are sandstones and sandy shales, and the middle member consists of interbedded limestone and shale beds. The sandstones are

well developed in only a few localities, these zones being represented in most places by sandy shale. The entire sequence of beds varies between 60 and 90 feet in thickness and in places perhaps still less. Probably 75 feet would be a fair estimate of the average thickness.

The basal sandstone of the Upper Okaw attains its greatest thickness in the southern part of the area, and is well displayed at the H. C. Cole Milling Company, south of Chester. Here the exposed section consists of black shale overlain by about 2½ feet of fine-grained, thin-bedded, brown quartz sandstone above which are about 15 feet of massive sandstone. Other exposures of the Tar Springs sandstone and sandy shale occur along the Mississippi bluff as far north as Riley Lake, about ½ mile east of Evansville, along the Evansville-Baldwin road and along Plum, Butter, and Ninemile creeks east of Okaw River.

The Vienna portion consists of interbedded gray to blue shale and hard, cherty, dark-blue limestone in layers of varying thickness, which usually contain abundant bryozoa and crinoid fragments. One of the best exposures is in the ravine which heads in the south part of the village of Ellis Grove, and other good exposures occur in the prison quarry and in the ravine which heads in the eastern part of Chester.

The upper sand, or Waltersburg member, is best developed as a quartz sandstone in the northern part of the area. The sandstone is dark brown and thin bedded, and because of two sets of parallel joints usually breaks into elongate blocks not unlike sticks of stove wood about 2–4 inches across and 12–20 inches long. The associated shales are sandy and brown to gray in color.

CRITERIA OF CORRELATION

The separation of the Okaw into at least two units is based on the disconformity which occurs in the midst of these strata, dividing them into a lower portion of middle Chester and an upper portion of late Chester age. The greatest variation in thickness in the Okaw is in the series of beds between the Marigold oölite, or the cherty, sandy horizon above the oölite, and the upper arenaceous portion, that is, in the Glen Dean division of the Lower Okaw. This variation was produced during an erosional interval, when the upper

portion of the Glen Dean was irregularly removed in parts of the area before the Tar Springs was deposited. This interpretation is substantiated by the varying thickness and lithology of the beds above and below the contact. Locally, the Tar Springs lies upon the massive quarry beds, and in other places the massive limestone is separated from it by intervening shale and limestone. In general, where the Tar Springs sandstone is best developed, the Upper Okaw is thickest, the Glen Dean thinnest, and the interbedded limestone and shale zone between the massive quarry ledge and the base of the sandstone is thin or absent.

The correlation of the Lower Okaw with the Golconda-Glen Dean portion of the standard Chester section is well established on paleontological evidence. The most diagnostic forms for correlation of these formations are species of the crinoid genus, *Pterotocrinus*. Two species, *P. capitalis* and *P. coronarius*, are limited in their occurrence to the Golconda throughout the Eastern Interior Basin and the Southern Appalachian province. These two species occur here only in the lower portion of the Lower Okaw, the beds below the cherty, sandy zone. Equally characteristic of the Glen Dean are *P. scapulatus*, *P. depressus*, *P. acutus*, and *P. bifurcatus*, all of which occur in considerable abundance in the upper portion of the Lower Okaw in many localities. The Golconda formation, in many places in southern Illinois and western Kentucky, also contains a characteristic faunule of gastropods and pelecypods, largely undescribed. This same assemblage is present in the lower portion of the Lower Okaw, especially in the Marigold oölite. Other common but not equally diagnostic species of the two formations are present in the Lower Okaw in great abundance.

The correlation of the Upper Okaw with the Tar Springs–Vienna-Waltersburg succession is not established quite so readily upon paleontological grounds. Unfortunately, the Vienna limestone upon which paleontologial correlation must be based, contains no characteristic species. The Vienna elsewhere, however, lacks the true guides of the Glen Dean, a condition equally true for the middle limestone and shale of the Upper Okaw. In many localities farther east the Vienna contains specimens of *Orthotetes kaskaskiensis* in great abundance, as well as large specimens of *Composita subquadrata*,

species which are never abundant in the Glen Dean. These same forms occur in the middle limestone and shale of the Upper Okaw, and though their presence is not conclusive evidence for correlation it is certainly suggestive.

The best evidence for correlation is found in lithologic and stratigraphic features. The middle member of the Upper Okaw consists of dark-blue, hard, cherty limestone and shale similar to the Vienna limestone elsewhere. The Chester sandstones commonly lack distinctive lithologic features useful for their identification, although locally there are exceptions to this rule. The Waltersburg sandstone is the only one which may be considered an exception almost wherever it occurs. In almost all exposures it possesses the property of breaking into elongate joint blocks resembling sticks of stove wood. This feature is characteristic of the upper sandstone of the Upper Okaw in localities where it is well developed.

Finally, the Upper Okaw consists of a limestone and shale member between two sandstone and arenaceous shale members, an arrangement of strata identical with the Tar Springs–Vienna-Waltersburg sequence elsewhere. The beds in both areas occur between definitely identified Glen Dean limestone below and Menard limestone above, a situation which would seem to admit of no logical interpretation other than approximate equivalency for them.

CONCLUSIONS

The evidence as given in the preceding pages leads to the following conclusions:

1. The original Okaw is a composite stratigraphic succession which is divided into two units by a disconformity.

2. Each of these units is mapable and worthy of at least formational rank.

3. The lower unit, here called the Lower Okaw, is of middle Chester age and correlates with that portion of the standard section included in the Golconda, Hardinsburg, and Glen Dean formations of southeastern Illinois and western Kentucky.

4. The upper unit, here called the Upper Okaw, is of late Chester age and equivalent to the Tar Springs, Vienna, and Waltersburg formations of the Chester farther east.

FOSSIL MARKINGS IN THE CARMELO SERIES (UPPER CRETACEOUS [?]), POINT LOBOS, CALIFORNIA

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ABSTRACT

Fossil markings of doubtful origin were found in strand deposits of the Carmelo series (Upper Cretaceous [?]) at Point Lobos, California. The purpose of this article is to show that some of the markings may have been formed by seaweed, a suggestion borne out by observations on modern strands. Associated fossil casts and tubular pits are described and organic agencies suggested as responsible for their origin.

INTRODUCTION

An interesting group of fossil markings which now are thought to have been formed by seaweed were found by the writer while studying the Carmelo series at Point Lobos State Park, California. These are the only fossils which have been found in this series, with the exception of some doubtful arenaceous Foraminifera. The markings will be described and an attempt will be made to show, from observations made on present-day beaches, how some of them may have been formed. Certain generic references will be made, but it should be understood that these are for the sake of comparison only.[1]

Point Lobos State Park lies immediately south of Carmel Bay, 115 miles south of San Francisco. The markings herein described may be seen at low tide in a small embayment about 1 mile south of Point Lobos proper. Exposed to wave action, these markings are being worn away rapidly.

The Carmelo series at this locality consists of the following types, in order of abundance:

1. Coarse, dark-colored conglomerate of well-rounded porphyry and granite pebbles.
2. Medium-grained, tawny-yellow, granitic sandstone with argillaceous cement. Rather thick bedded. Maximum development of seaweed impressions and ripple marks.

[1] To Drs. W. A. Setchell, R. W. Chaney, C. W. Gilmore, C. L. Camp, and Howel Williams is due acknowledgment for many helpful suggestions and criticisms. E. W. Galliher visited the locality with the writer and very kindly permitted the use of one of his photographs.

3. Thin-bedded, black, somewhat sandy shale, interbedded with the sandstone. Contains casts of seaweed stems.

The total thickness is estimated to be approximately fourteen hundred feet. This series is found in depositional and fault contact with the Santa Lucia (Coast Range) granite of Jurassic (?) age, and is unconformably overlain by Pleistocene or Recent terrace deposits. In the first description of these rocks by Lawson,[2] the series was referred to the Upper Eocene (Tejon) on the basis of a lithologic correlation, since no fossils were found. Later work by Hawley[3] and Trask,[4] however, has shown that the age is probably Upper Cretaceous (Chico). Shallow-water deposition is clearly shown, and the ripple-marked sandstone gives evidence of a sandy beach near wave line. The ripple marks are symmetrical and slightly modified by current action or swirling waters. Rill marks and "mud-flows" are preserved to a smaller extent.

SEAWEED IMPRESSIONS

The seaweed impressions which are superposed on the ripple marks, consist of two rows of semibulbous shaped indentations separated by a central "stem" of disturbed sand, $\frac{3}{4}$–$1\frac{1}{4}$ inches wide (Figs. 1 and 2). The crest of the stem lies flush with the undisturbed sand bordering the impressions. The semibulbous impressions have their maximum diameter slightly anterior to the middle of their longitudinal axes. Averaging about an inch in length, $\frac{3}{8}$–$\frac{1}{2}$ inch in maximum diameter, the impressions are from $\frac{1}{4}$ to $\frac{1}{2}$ inch deep. The longitudinal axes are inclined at an angle of approximately 40° to the "stem," with the points of attachment of the lateral indentations nearly opposite each other, rather than staggered or offset. Most of the impressions have a frequency of 11–13 per foot and have been traced for a maximum length of 4 feet.

The markings are approximately normal to the direction of the ripple marks, i.e., parallel to the direction of movement of the water,

[2] A. C. Lawson, "Geology of Carmelo Bay," *Univ. Calif. Publ., Bull. Dept. Geol.*, Vol. I (1892), pp. 18–21.

[3] H. J. Hawley, "Stratigraphy and Paleontology of the Salinas and Monterey Quadrangles, California," *Bull. Geol. Soc. Am.*, Vol. XXVIII (1917), p. 225.

[4] P. D. Trask, "Geology of Point Sur Quadrangle, California," *Univ. Calif. Publ., Bull. Dept. Geol. Sci.*, Vol. XVI, No. 6 (1926), pp. 141–42.

as shown in Figures 1 and 2. Branching is characteristic, and in many cases the branches have arcuate or sinuous trends, as though the object had swayed back and forth in the moving water. Where this branching occurs, no obliteration or duplication of markings is

FIG. 1.—Seaweed impressions on ripple-marked Carmelo sandstone. Irregular "leaf-growth" marking in lower center. Pitted surface in upper center and right-hand corner.

found at or below the point of junction with the "stem." Many of the impressions cross each other, the upper partly obliterating the lower for several inches on either side (see above and left of center, Fig. 1), as though the body had moved from side to side before coming to rest on the previously formed impression. Of further interest is the peculiar irregular marking seen in the lower center of Figure 1, which resembles in some respects the leafy growth of certain modern seaweeds.

When first seen, these markings were thought to have been formed by the passage of some animals over the sand. Further examination, however, revealed several points militating against this interpretation, the most important of which are: first, the marks could not be traced to any known living or fossil animal; second, where branching occurs, there is no superposition of marks, such as

FIG. 2.—Seaweed impressions and pits on ripple-marked sandstone. Scale approximately ¼ natural size. (Phot. by E. W. Galliher.)

would be expected in the case of animals leaving or coming onto a common trail; third, in the sinuous portions of the markings there is no pronounced change in character, such as the increased frequency of individual impressions commonly observed on the inner side of trails made by animals following a curved path.[5]

The markings described are most closely simulated by the various forms of *Nereites*, *Crossopodia*, *Myrianites*, etc., described from Paleozoic rocks, as determined from a study of the extensive ichno-

[5] J. W. Dawson, "On the Fossils of the Genus *Rusophycus*," *Can. Nat. and Geol.*, n.s., Vol. I (1864), p. 367; Sidney Powers, "Gastropod Trails in Pennsylvanian Sandstones in Texas," *Amer. Jour. Sci.*, 5th ser., Vol. III (1922), p. 104.

logical literature. Ludwig,[6] Schimper,[7] Nicholson and Etheridge[8] regarded these forms as imprints of marine plants, but Emmons,[9] Nathorst,[10] Delgado,[11] and many others believed that animals were responsible. In either case, the imprints figured by these writers differ in many characteristics from those of the Carmelo series, and all of them are of much smaller dimensions, many being only a tenth as large. Powers[12] described markings on sandstones of Pennsylvanian age, which he believed were caused by seaweed dragged across the sand, and of others produced by the waving to and fro of seaweed in moving water. None of these imprints bear any resemblance, however, to the markings under consideration, and the smaller imprints apparently were produced by other types of seaweeds in a different environment. Brown[13] observed the behavior of seaweeds in the vicinity of beaches and in shallow waters, and concluded:

"... it is evident that markings closely simulating molluscan and annelid trails *may* be produced without animal agency, and even such markings .... mistaken for those made by fishes, crustaceans, or reptiles may be similarly produced."[14]

Although Brown's remarks referred largely to markings produced by the dragging of rocks, etc., over a shallow bottom by seaweed, he indicated that many observers have been too eager to describe the

[6] R. Ludwig, "Fossile Pflanzenreste aus der paleolithischen Formation von Dillenburg," *Paleontographica*, Band VII (1869), p. 139.

[7] W. P. Schimper, "Traité de paléontologie végétale," Vols. I–III (Paris, 1869–74).

[8] H. A. Nicholson and R. A Etheridge, "A Monograph of the Silurian Fossils of the Girvan District in Ayshire," Fasc. III (1880), p. 311.

[9] E. Emmons, *American Geology*, Part 6, *Agriculture*, Vol. I (1857).

[10] A. G. Nathorst, "Om spår af några evertebrerade Djur m. m. och deras paleontologiska betydelse," *Kongl. Svenska. Vet. Akad. Handlingar*, Band XVIII, No. 7 (1881), pp. 25–44.

[11] J. F. N. Delgado, "Étude sur les fossiles des schistes à de San Domingos," *Terrains-Paléozoïques du Portugal, Comm. du Serv. Géol. Portugal* (1910), pp. 1–8.

[12] Strand Markings in the Pennsylvanian Sandstones of Osage County, Oklahoma," *Jour. Geol.*, Vol. XXIX (1921), pp. 69. 70, 73.

[13] A. P. Brown, "The Formation of Ripple Marks, Tracks, and Trails," *Proc. Acad. Nat. Sci. Phila.*, Vol. LXXIII (1912), pp. 536–47.

[14] *Ibid.*, p. 547.

fantastic wanderings of some animal, rather than to consider the possibility of other causes. Likewise the observations of Williamson[15] on strand lines present many interesting points concerning tracks, trails, and markings. His descriptions and illustrations of rills on modern beaches producing plant like impressions are very striking. Also the markings described by Clarke[16] show further the types of *problematicae* that may be formed on strand lines.

Experiments made by the writer on a beach with modern *Egregia* produced markings not essentially different from those in the Carmelo series. An *Egregia* with the bladders well developed was artificially stranded within reach of the waves on a beach composed largely of quartz sand. The plant was laid down in a curved position, with its general trend oblique to the direction of movement of the water. After the third or fourth wave had washed over the plant, it had assumed a position similar to that seen in the fossil markings, viz., parallel to the movement of water. As the backwash from succeeding waves rushed by the stranded form, the individual bladders moved up and down in rapid succession, beating a staccato on the sand. This action was examined closely, and it was found that the bladders were momentarily raised by the force of the water on the curved lower surface. With the bladder thus elevated, the water rushed under the body, removing a small amount of sand before the bulb dropped back again. Each backwash caused a repetition of this rapid flapping until the depressions reached a depth of approximately one-half their diameter.

The behavior of the plant in the advancing waves was different from that in the backwash. When the waves advanced, the water was of much greater depth, but during the backwash the plant was rarely submerged. Once the scouring action of the receding waves had removed a small amount of sand from under the bladders, the pressure of the deeper water brought in by the advancing waves apparently caused the bladders to remain relatively stationary, em-

[15] W. C. Williamson, "On Some Undescribed Tracks of Invertebrate Animals from the Yoredale Rocks, and on Some Inorganic Phenomena Produced on Tidal Shores, Simulating Plant Remains," *Manchester Lit. and Philos. Soc. Mem.* 3d ser., Vol. X (1887), pp. 19–29.

[16] J. M. Clarke, "Strand and Undertow Markings of Upper Devonian Time as Indications of the Prevailing Climate," *N.Y. State Mus. Bull. 196* (1917), pp. 199–210.

bedded in the rapidly forming depressions, despite the somewhat greater velocity of the water. It was difficult to note the action of the bladders in the advancing waters, but several observations were made immediately following the breaking of a wave, and it was found that the bladders had not changed their positions. If they did move during the rush of incoming water, they resumed their former position before observation was possible. The concavity did not appear to be disturbed to any determinable amount.

Upon careful removal of the plant from the sand, the results obtained bore striking similarity to the markings observed in the Carmelo series. The area covered by the stem did not have a groove or furrow, but the sand appeared partially washed away from the outer edges leaving a ridgelike feature instead. In various details these results differed from the fossil markings, but these differences may have been due partly to the character of the sand, for this was almost wholly made up of quartz grains, and was lacking in such argillaceous material as that in the Carmelo sandstone. Powers'[17] conclusions on various trails formed by the same animal traveling over a different type of sand well may be applied here, with certain modifications. The amount of micaceous material present was the variable factor involved in the gastropod trails studied by Powers, but in this case the amount of mica is negligible, both in the Carmelo and recent sands.

In view of the results obtained from the experiments, and the various evidences against animal origin, the writer believes the Carmelo markings to have been formed by an *Egregia*-like seaweed under conditions somewhat similar to those actually observed.

SEAWEED CASTS

In the black sandy shale interbedded with the sandstone were found many peculiar, long, narrow bodies composed of sand, lying parallel to the bedding plane (Fig. 3). Almost all of these forms are branched. In cross section the majority are elliptical, but some are circular, and it is believed the elliptical forms are due to compression by overlying sediments. This is borne out by the deforma-

[17] "Gastropod Trails in Pennsylvanian Sandstones in Texas," *Amer. Jour. Sci.*, *op. cit.*, pp. 103–6.

tion of the underlying beds (fig. 3*a*). The maximum diameter is $\frac{5}{8}$ inch, and the minimum diameter, always perpendicular to the bedding planes, is from $\frac{1}{4}$ to $\frac{3}{8}$ inch. Many of the casts though interrupted are alined, and assuming the separate parts formerly to have been continuous, the longest measured was 3 feet. The branches are relatively short, attaining a length of $1\frac{1}{2}$–3 inches and their ends are somewhat tapered. Only rarely do the branches occur on both sides of the stem. A bulb-like swelling was found in one specimen, apparently at the terminus. Dr. Setchell[18] pointed out the similarity of these characteristics to those of the modern *Pelagophycus* or Elk-kelp. Paleozoic fossils resembling the Carmelo forms have been described and figured as plants under the name *Fucoides* by Hall,[19] James,[20] and many others. The conformity with the bedding planes and characteristic branching of the forms described here differs from most observed animal burrows. It is suggested, therefore, that the Carmelo casts are the result of the burial of seaweed, its removal, and the subsequent infilling of the cavity, which was later deformed while sediment was still in semiplastic state.

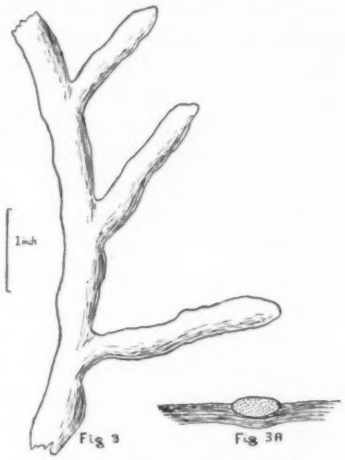

FIG. 3.—Drawing of a portion of seaweed cast in shales, showing characteristic branching.

FIG. 3*a*.—Cross section of seaweed cast, illustrating elliptical form and deformation of underlying shales.

Another fossil in the black shale is in part a sand cast similar to those described above, but is lacking in branches (Fig. 4). The cast measures about $2\frac{1}{2}$ feet long and $\frac{3}{8}$ inch wide. Terminating abruptly,

[18] W. A. Setchell, oral communication.

[19] James Hall, *Paleontology of New York: Nat. Hist. of New York*, Part VI, *Paleontology*, Vol. II (1852).

[20] J. F. James, "Studies in Problematic Organisms, No. II, the Genus *Fucoides*," *Jour. Cinn. Soc. Nat. Hist.*, Vol. XVI (1893), pp. 62–82.

it is followed in direct alinement by a groove or furrow 2 feet long and $\frac{1}{2}$ inch deep. Within 2 inches of the end of the cast the groove widens to 1 inch across, but beyond this point its sides are parallel. On the bottom and sides of the groove are numerous pits, $\frac{1}{4}$ inch in diameter and $\frac{1}{8}$ inch deep, spaced at intervals of $\frac{3}{8}$–$\frac{1}{2}$ inch. Both cast and groove are straight, with the exception of a slight curve in the latter, and both conform with the bedding plane.

FIG. 4.—Drawing of a portion of sand cast and associated groove or furrow with pitted surface.

Two possibilities may be considered. First, the cast may represent the shallow burrow of a marine animal, and the groove either the trail of the animal as it came to the surface, or the imprint of its body after death. Even though animals of burrowing type are known to be able sometimes to confine themselves into spaces smaller than the normal dimensions of their body, it is difficult to believe that the same form which produced the furrow or imprint could have been confined in a tube $\frac{5}{8}$ inch smaller (or less than one-half) in diameter. Of course, it is possible that the dormant body may have been flattened out before complete decomposition so as to give an imprint of somewhat greater width. Second, the cast may represent the barren stem of a marine or terrestrial plant, and the groove the portion of the plant covered with buds, leaves, or similar growth. The second consideration is more probable because of the association with supposed plant impressions and casts, conformity with bedding planes, and the marked increase in diameter of the furrow over that of the cast.

TUBULAR PITS

In the ripple-marked sandstone are numerous pits or tubes (upper right corner, Fig. 2; upper center and right, Fig. 3) occurring

either singly or in groups of ten to fifteen. In vertical cross section the pits cut the bedding at right angles for depths of 2–3 inches, the diameter decreasing from $\frac{3}{16}$ inch at the surface to $\frac{1}{16}$ or $\frac{1}{8}$ inch at the rounded base. The tubes are filled with sand from the overlying bed, which does not differ markedly in its composition from the enclosing material, but iron oxide staining accentuates the outline.

Somewhat similar occurrences have been described as worm-borings (*Scolithus*, *Sabellaria*, *Arenicola*, etc.) by Dawson,[21] James,[22] Richter,[23] and numerous others. Roots and stems of marine algae and higher plants have been regarded by some authors as responsible for similar forms. Kindle[24] produced pits and mounds in fine muds by allowing sediment to settle rapidly, causing vertical currents. Sand holes in modern strands have been described by Palmer[25] as air vents formed by the action of waves passing over stratified beach material. These, however, are not vertical with the exception of places where they perforate the surface.

Can the Carmelo pits have been occupied by algal roots or stems? It is true that algae do not grow on bottoms covered with pure drifting sand, but the abundance of supposed plant material associated with the pits lends strength to the possibility of plant origin. The amount of argillaceous material in the sand may have been sufficient to support growth, or possibly some plants were washed in by currents and waves, as in the case of some of the previously described forms. It is doubtful whether the vertical currents such as those obtained by Kindle in his laboratory study could be formed with sufficient velocity to move the medium-sized sand grains and the argillaceous material from a depth of $3\frac{1}{2}$ inches, primarily be-

[21] "Notes on Some Supposed Burrows in Laurentian Rocks of Canada," *Quart. Jour. Geol. Soc. London*, Vol. XXII (1866), pp. 608–9.

[22] "Studies in Problematic Organisms, Part I, the Genus *Scolithus*," *Bull. Geol. Soc. Amer.*, Vol. III (1892), pp. 32–44.

[23] Rudolph Richter ,"Ein devonischer Pfeifenquartzit," *Senckenbergiana*, Band II, Heft 6 (1920), pp. 215–35; "Scolithus, Sabellarifex, und Geflechtquartzite," *ibid.*, Band III (1921), pp. 49–52.

[24] E. M. Kindle, "Diagnostic Characteristics of Marine Clastics," *Bull. Geol. Soc. Amer.*, Vol. XXVIII (1917), pp. 909–10.

[25] R. H. Palmer, "Sand Holes of the Strand," *Jour. Geol.*, Vol. XXXVI (1928), pp. 176–80.

cause the horizontal movement of the water, indicated by the presence of ripple marks, would not allow the vertical currents to act long enough in one place. The air vents noted by Palmer have a very irregular form in contrast with the uniform vertical tubes of the Carmelo series, though it is not impossible that a change of environment from that discussed by him may explain the difference. Several descriptions of worm tubes seem to apply to the Carmelo pits, notably *Arenicola*, *Histioderma*, *Diplo-* and *Monocraterion* which are described by Richter[26] as "Tubular holes normal to the bedding plane; cavities that held the cylindrical bodies of tubicolous annelids."

But the evidence seems insufficient to the writer to assign with certainty any of the above possible origins to the tubes or pits in the Carmelo series. He prefers to conclude that they are more probably of organic, rather than mechanical, origin.

[26] "Observations on Organisms and Sedimentation on Shallow Sea Bottoms," *Amer. Midland Nat.*, Vol. XI (1928), p. 241.

THE ISOTOPIC COMPOSITION OF THE LEADS AT GREAT BEAR LAKE

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ABSTRACT

The isotopic composition of five samples of lead from the radium mines of Great Bear Lake indicates that the lead within the pitchblende veins is all of radioactive origin, even including that which now exists as galena, though a galena occurring close to a pitchblende vein is composed of ordinary lead contaminated with radioderived lead. The data raise unusual problems.

The work reported here was part of the investigations undertaken by the Committee on the Measurement of Geologic Time of the National Research Council, of which Professor A. C. Lane is chairman and the author one of the members participating.

The mineral situation occurring at the pitchblende deposits at La Bine Point, Great Bear Lake, Northwest Territories, Canada, is somewhat complex and unusual, and this novel condition seems to extend to the isotopic composition of the lead associated with the radioactive deposit there.

It is now well established that in ordinary or primal lead the order of abundance of the three principal isotopes is Pb 208, Pb 206, Pb 207, whereas all samples of lead so far examined which were derived from uranium minerals have these isotopes occurring in the order Pb 206, Pb 207, Pb 208. This fact distinguishes ordinary (primal) lead from radioderived lead and may furnish a method of detecting a contamination of the one by the other. This is of the utmost importance wherever an age determination is contemplated.

Considerable work has been done on lead samples extracted from various parts of the pitchblende deposits at La Bine Point, Great Bear Lake, and the value recently found for the atomic weight of one of these leads is somewhat unusual.[1]

[1] J. P. Marble, "The Atomic Weight of Uranium Lead from Great Bear Lake, N.W.T., Canada Pitchblende," *Jour. Amer. Chem. Soc.*, Vol. LVI (1934), p. 854. Other determinations are now in progress.

In this paper are presented certain facts and interpretations derived from studies of some samples of lead from this deposit which are the result of the work of a number of co-operating investigators, and which seem sufficiently suggestive to warrant recording and further verification.

Mr. H. S. Spence,[2] of the Mines Branch of the Canadian Department of Mines, furnished the Committee with a number of samples of pitchblende and other minerals from this deposit, among which were:

I. Pitchblende from the siliceous portion of No. 1 Vein taken from Pit No. 1 of that vein.
II. Pitchblende from the siliceous portion of No. 2 Vein.
III. Pitchblende from the carbonate portion of the same No. 2 Vein.
IV. Galena from a depth of 15 feet within the pitchblende of No. 2 Vein.
V. Galena from a chalcopyrite-galena band in the country rock cut by the No. 2 Vein.

This last sample (V) was found adjacent to, but not in, the pitchblende vein proper. Spence states: ". . . . it came from within a foot or two of the pitchblende vein, on its north side."[3] The leads, with the exception of sample II, were extracted from the various mineral samples by Dr. J. P. Marble[4] while engaged in the determination of their atomic weights; the isotopes and their orders of abundance were determined by Dr. Fred Allison and his associates as part of a study of the isotopic composition of various samples of lead from different sources.[5] The order of abundance of the principal isotopes of these leads, together with other significant data, is shown in Table I. It will be observed that the leads of samples I, II, III, and IV are all typical uranium leads, i.e., the three principal isotopes occur in an order of abundance: Pb 206, Pb 207, Pb 208, and that

[2] "The Pitchblende and Silver Discoveries at Great Bear Lake, Northwest Territories," *Bull. No. 727–3 Dept. Mines, Can.*, being Section 111 of *Investigations in Mineral Resources and the Mining Industry, 1931*, pp. 55–92.

[3] Letter to the author, July 24, 1933.

[4] *Op. cit.*

[5] E. Bishop, M. Lawrenz, and C. B. Dollins, "Lead Isotopes," *Phys. Rev.*, Vol. XLIII (1933), p. 43; and C. S. Piggot, "Isotopes of Uranium, Thorium and Lead and Their Geophysical Significance," *ibid.*, pp. 51–59.

the less abundant isotopes all belong to the U 238 (uranium) series. Apparently the less abundant lead isotopes produced by the other series (U 240, U 239, U 237) occur in exceedingly small amounts.

TABLE I

ISOTOPIC COMPOSITION OF SAMPLES OF LEAD FROM THE GREAT BEAR LAKE RADIUM DEPOSITS

Sample No.	Type Deposit	Mineral of Origin	Principal Isotopes of the Leads in Order of Abundance	Location of Mineral of Origin
I.....	Siliceous	Pitchblende	206 207 208	Pit No. 1, Vein No. 1
II.....	Siliceous	Pitchblende	206 207 208 214	Vein No. 2, western portion
III.....	Carbonate	Pitchblende	206 207 208 214	Vein No. 2, eastern portion, 1,200-foot section
IV.....	Carbonate	Galena	206 207 208 214 202 210	Vein No. 2, Pit No. 14 (eastern portion). 15 ft. depth. Galena only, but within the pitchblende vein
V.....	Siliceous	Galena	208 207 206 212	Vein No. 2, Pit No. 2 (western portion). Galena adjacent to but not in pitchblende vein

This indicates that although some Pb 208 is present, produced by the U 240 or thorium series, there is exceedingly little of this series left now, and the other lead isotopes belonging to this series are existing in a lower concentration than the less abundant members of the dominant, U 238, series. In other words, these four leads are examples of exceptionally pure uranium lead. This conclusion is substantiated by the atomic weight determination recently completed

by Marble, which indicates that contamination by common (primal) lead cannot be greater than 1 part in 5000.

Sample V, however, is obviously not like the others. Its isotopic composition is extremely interesting, and is unique, when compared with any lead that has been reported to date. It is obviously not a uranium lead (Pb 206, 207, 208), nor is it a typical ordinary (primal) lead (Pb 208, 206, 207). The two most abundant isotopes are Pb 208 and Pb 207, the first representing the thorium series (or U 240) and the second the actinium (or U 239) series. The next in order of abundance is Pb 206, which is the principal lead of the uranium (U 238) series and this is the only lead belonging to this series which exists in sufficient concentration to be detected under the conditions of the test, while the next isotope is Pb 212, another member of the thorium series. It is significant that in the lead from the other galena, occurring *within* the pitchblende, all the less abundant isotopes belong to the U 238 series, whereas this galena from the rock adjacent to the pitchblende vein contains none such so abundant as this member of the U 240 or thorium series. In ordinary (primal) lead the abundance of the Pb 207 isotope is normally less than that of the Pb 206, so that in this particular case it is an open question whether the dominant lead was a thorium lead or an ordinary lead, which has become contaminated by uranium lead. Chemical analyses have shown exceedingly small amounts of thorium in these pitchblendes and both the isotopic compositions of the leads and the atomic weights substantiate this evidence, so that the first of the foregoing possibilities would seem to be ruled out. Therefore, it would appear that this sample V represents a galena composed of ordinary (primal) lead occurring in the usual manner in a vein in the country rock, but so close to the pitchblende vein that it has become considerably contaminated by the uranium lead produced there. But the galena of sample IV is a uranium lead galena and an unusually pure one.

From deductions based on the isotopic evidence here presented the conclusion seems reasonable that there are two galenas, the one composed of ordinary or primal lead combined with sulphur, but somewhat contaminated by radioderived lead, whereas the other

galena is composed of a lead which seems to be entirely radioderived (very largely from one particular radioactive series) and must have entered into combination with the sulphur subsequent to its formation.

These considerations open up interesting geologic, petrographic, and mineralogic aspects of the evidence thus far available and of the interpretation here offered. The author hopes that they will be discussed by specialists in these fields.

REDEPOSITION OF MICROSCOPIC DEVONIAN PLANT FOSSILS

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ABSTRACT

Sporangites huronensis, a Devonian plant spore, has been redeposited in the present-day bottom sediments of Lake Michigan, having been eroded from an intermediate resting place in glacial till. The occurrence of the spores in certain widely distributed clay deposits as practically the only organic remains illustrates the possibility that redeposited micro-fossils may lead investigators to an erroneous determination of the age of a deposit.

An unusual case of redeposition of micro-fossils is found in the discovery of *Sporangites huronensis*, a Devonian plant spore, in the present-day bottom deposits of Lake Michigan. These plant spores were originally deposited in the marine black shales of Middle Devonian age (Hamilton) over a large area which includes much of Michigan, Ohio, and Kentucky, and extends into a number of neighboring states. The spore material constitutes an important percentage of the rock, and is a source of the oil which the rock yields on distillation.

Sporangites huronensis, which is believed to be a macrospore of some lycopodiaceous tree,[1] is made up of resinous material. When viewed by transmitted light it is usually yellow, or amber colored, and shows little or no structure with the exception of the fact that the walls can be distinguished from the internal cavity. The shape is discoid, but varies somewhat according to the manner and degree of flattening which has taken place. The spores average 0.21 millimeters in diameter. They were discovered in the Chicago city water supply and in the glacial deposits in the vicinity of Chicago as early as 1865, but were not reported from this locality until 1884, when Johnson and Thomas gave their paper on "The Microscopic Organisms in the Bowlder Clays of Chicago and Vicinity" before the Chicago Academy of Sciences.[2] Meanwhile, in 1871, Dawson[3] had

[1] J. W. Dawson, "On Spore Cases in Coals," *Amer. Jour. Sci.*, Vol. I, 3d Ser. (1871), p. 258.

[2] H. A. Johnson and B. W. Thomas, *Bull. Chi. Acad. Sci.*, Vol. I (1884), pp. 35–40.

[3] *Op. cit.*, pp. 256–63.

described and named the spores, which he had found in the Devonian black shales of Kettle Point, in Lake Huron. Dawson's work led Johnson and Thomas to the discovery of the spores in pebbles of Devonian shale which were included in the till. Thomas traced the fossils in the glacial till of the western shore of Lake Michigan from the Indiana state line to Kenosha, Wisconsin, and found them in a sample of till from Bloomington, Illinois, 105 miles southwest of Chicago. Recent investigators of the glacial deposits of the Chicago region have also observed that the spores are common constituents of the till.[4]

Evidence that *Sporangites* is widely distributed in the present-day sediments of the southern part of Lake Michigan has been found by the writer in his study of the bottom deposits of Lake Michigan. The spores, which apparently are confined to the finer-grained deposits, are found in the following localities: (1) in the few areas of silt which occur in the lake near Chicago; (2) in an area of silt a few miles northeast of Hammond, Indiana; (3) in a zone of silt a few miles offshore at the extreme southern end of the lake; (4) in a zone of silt which parallels the eastern shore; (5) in a fine-grained clay in the middle of the lake, 40 miles from shore, in 468 feet of water. They are undoubtedly present in intermediate areas which the writer has not sampled.

It is believed that the main source of *Sporangites* for the present-day sediments in the southern basin of the lake is the glacial till on its western shore and on the adjacent bottom. The Devonian shale does not outcrop on or near shore in the region, and the fossils were not found in a number of till samples from the vicinity of St. Joseph, Michigan, on the eastern shore, which were put at the writer's disposal by Dr. W. C. Krumbein.

The widespread occurrence of *Sporangites* on the lake bottom is not surprising, because the low specific gravity and disk-like shape of the fossils enable the waves and currents of the lake to keep them

[4] W. C. Krumbein, "Textural and Lithological Variations in Glacial Till," *Jour. Geol.*, Vol. XLI, (1933), pp. 382–408.

Mr. E. H. Stevens, of the University of Chicago, has found the spores in great abundance in certain Chicago tills, and has kindly supplied the author with a sample.

in suspension indefinitely.[5] Though these microscopic plant fossils are in deposits of the third generation, the spores taken from Lake Michigan sediments usually appear as fresh as those separated from pebbles of the original black shale.

In certain of the silt areas, on both the east and west sides of Lake Michigan, *Sporangites* is found mingled with the remains of a modern fresh-water fauna which includes such forms as the Arthropod genus, *Gammarus*. On the other hand, the spores are practically the only organic remains in the dark-colored, fine-grained clay which covers many square miles in the deeper parts of the lake. The principle illustrated by this phenomenon is obvious. Redeposited micro-fossils which show little or no wear may easily lead investigators to an erroneous determination of the age of a deposit, when such fossils are not accompanied by remains of organisms which lived in the waters where the deposit was formed.

Sporangites, because of its tough, resinous, water-resisting qualities, is unusually fitted to withstand the physical and chemical processes of destruction which it has encountered in more than one cycle of sedimentation, but microscopic animal fossils such as Foraminifera, though relatively fragile, may also be redeposited without showing any considerable amount of wear.

[5] Confirmed by collecting the spores from the tap water in Chicago. The samples of bottom deposits examined in the laboratory were not exposed to contamination by tap water.

GEOLOGY OF THE THRUST FAULT NEAR GARDINER, MONTANA

CHARLES W. WILSON, JR.
Vanderbilt University

ABSTRACT

The Gardiner thrust fault has been mapped in detail from the west side of Cinnabar Mountain, Montana, where it appears from under a cover of Tertiary volcanics, southeastward to a point 3 miles east of Mount Everts, Yellowstone National Park, where it passes under the volcanics. The fault plane dips to the northeast at approximately 35°, and is characterized by numerous subsidiary "slicings," also dipping to the northeast, beneath the major thrust plane. This high-angle, northeastward-dipping thrust forms the southwestern margin of the Beartooth Mountain uplift of which the low-angle, southwestward-dipping Beartooth thrust forms the northeastern margin. A genetic relationship is thought to exist between the thrusting and the intrusion of the dacite and andesite porphyries found within a close proximity of the fault plane. At some time following the development of the present topography basaltic extrusions came up along the fault plane. At a still later date hot springs issued from the fault plane, resulting in the deposits of travertine near Gardiner.

INTRODUCTION

During the summer of 1933 the writer took part in the co-operative project of geological research that has been carried forward in the Yellowstone-Beartooth-Bighorn region of Montana and Wyoming by a group of geologists with headquarters at Red Lodge, Montana.[1] As a unit in this comprehensive program a planetable map of about 40 square miles was made of an area extending southeastward from Cinnabar Mountain, Park County, Montana, along the Yellowstone River, through Gardiner, Montana, and continuing to include the area between Mammoth Hot Springs, Yellowstone National Park, and the Yellowstone River. This area lies along the Livingston-Yellowstone Park highway that follows the Yellowstone River from Livingston to Gardiner, and the Gardiner River from Gardiner to Mammoth Hot Springs.

[1] W. T. Thom, Jr., and R. M. Field, "The Advancement of Geology through Co-operative Research," *Sci.*, Vol. LXXII (August 1, 1930), pp. 117–18; W. H. Bucher, W. T. Thom, Jr., and R. T. Chamberlin, "Geologic Problems of the Beartooth-Bighorn Region," *Geol. Soc. Amer.*, Vol. XLIV (1933), pp. 75–77; W. H. Bucher, R. T. Chamberlin, and W. T. Thom, Jr., "Results of Structural Research in the Beartooth-Bighorn Region, Montana and Wyoming," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XVII (No. 6, 1933); W. T. Thom, Jr., and R. M. Field, "Geologic Research near Red Lodge, Montana," *Sci.*, Vol. LXXVIII (August 4, 1933), pp. 103–5.

The purpose of the project was the study and detailed mapping of the Gardiner thrust fault and the associated faults in order to understand better the tectonic development of the major structural features of the surrounding region.

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FIG. 1.—Looking north down Gardiner River from Mammoth Hot Springs. Exposures of Carlile-Niobrara, Telegraph Creek, and Eagle on the east side of road in foreground. The valley of Yellowstone River in near background, beyond which may be seen the travertine and basalt capped terrace just north of Gardiner and Cinnabar Mountain beyond the west end of the terrace.

Professors Bucher, Chamberlin, and Thom had previously been impressed with the probable significance of the Gardiner thrust in relation to the origin of the Beartooth Mountain uplift, and it was at their suggestion that the field work was done.[2]

[2] Work in Yellowstone Park was done after consultation with Dr. C. M. Bauer, Park Naturalist for Yellowstone National Park. Every possible assistance in the prosecution of the work was given by Dr. Bauer and by others of the National Park Service who were kept informed as to the progress of the study and of the results being

STRATIGRAPHY

The rocks exposed within the area mapped range in age from pre-Cambrian to Quaternary. All of the intervening systems with the exception of the Silurian are represented. The different formations will be listed below.[3]

Quaternary

Alluvium
Glacial deposits
Travertine
Basalt

Tertiary

Volcanic breccias, flows, and agglomerates

Tertiary (?)

Reese Creek. Light-colored sandstone and conglomerate composed of water-worn volcanic material.

Cretaceous

Judith River. Alternating dark-green, olive-green, and black shale; brown carbonaceous shale and thin coal seams; light- to dark-buff sandstone which occasionally weathers green; bentonite beds; and two lenses of conglomerate composed of water-rounded volcanic boulders and filling stream channels... 1,204 feet (plus)

Parkman. Massively bedded, light-gray sandstone with several partings of dark-gray shale..... 390 feet

Claggett. Alternating dark-gray shale or mudstone; green bentonitic shale; light-gray sandstone; and dark-gray sandstones that weather greenish brown..... 648 feet

Eagle. Sandstones interbedded with shale and coal. Massive sandstone member (Virgelle) forms the base of the formation... 408 feet

Telegraph Creek. Thinly bedded, gray sandstone interbedded with blue sandy shale..... 318 feet

Carlile-Niobrara. Black shale, locally sandy..... 1,275 feet

Frontier. Thinly bedded, black, sandy shale interbedded with several light-gray quartzites and bentonite beds..... 300 feet

Mowry. Light-gray to black, sandy shale and a massive quartzite. 210 feet

obtained. Drs. C. M. Bauer, R. T. Chamberlin, L. C. Glenn, and W. T. Thom, Jr., read the manuscript and offered useful suggestions. Messrs. Willard Parsons, A. E. Whalley, and R. C. Doolittle efficiently assisted in making the planetable map, and to them the writer wishes to make full acknowledgments.

[3] For a more complete description of this section the reader is referred to a geological note by Charles W. Wilson, Jr., *Bull. Amer. Assoc. Petr. Geol.*, Vol. XVIII (1934), pp. 368–74.

Thermopolis. Black to dark gray, sandy shale with sandstones near the middle of the formation	685 feet
Cloverly:	
Dakota (?) Massive, light- to dark-gray sandstone	88 feet
Fuson (?) Varicolored shales and fine-grained, gray limestones	260 feet
Lakota (?) Massive sandstone and conglomerate	104 feet
Morrison. Varicolored shales and sandstones	228 feet
Jurassic	
Ellis. Olive, green, gray, and black shale with an arenaceous limestone at the top and a massive sandstone at the base	484 feet
Triassic	
Chugwater. Yellow sandstones and red, sandy shale	137 feet
Permian	
Phosphoria. Brown and black, phosphatic sandstones and fine-grained, siliceous limestone	167 feet
Pennsylvanian	
Tensleep. Massive, cross-bedded sandstone	130 feet
Amsden. Yellow, greenish gray, red, and purple shales, interbedded with sandstones and limestones	161 feet
Mississippian	
Madison. Massive limestone	1,100 feet
Devonian	
Three Forks. Gray, earthy, sandy shale; gray, sandy limestone: and black limestone	122 feet
Jefferson. Black limestone	116 feet
Ordovician (?)	
Bighorn (?) Light-gray limestone and dolomite	126 feet
Cambrian	
Not exposed in its belt of outcrop on Cinnabar Mountain. Presence of Cambrian was recognized by its position between the Bighorn dolomite and pre-Cambrian granite, and also by the finding of many fragments of Flathead quartzite.	
Pre-Cambrian	
Granite, granitic gneiss, and mica schist. In the vicinity of the thrust dacite and andesite porphyries are common.	

STRUCTURE

GARDINER THRUST FAULT

Introduction.—The Gardiner thrust fault appears from under a cover of Tertiary volcanics on the northwest side of Cinnabar Mountain and is traceable for a distance of 13 miles before it again goes under the volcanics 3 miles east of Mount Everts, Yellowstone

National Park. The fault was so named because it passes within a half-mile of Gardiner, well known as the northern entrance to the Park.

Regional aspects.—This thrust forms the central portion of a northwest-southeast structural line which extends across the south-

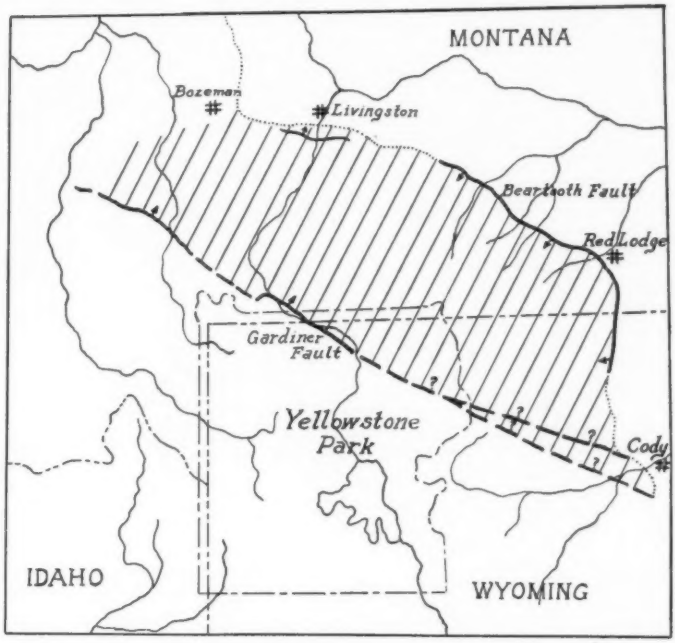
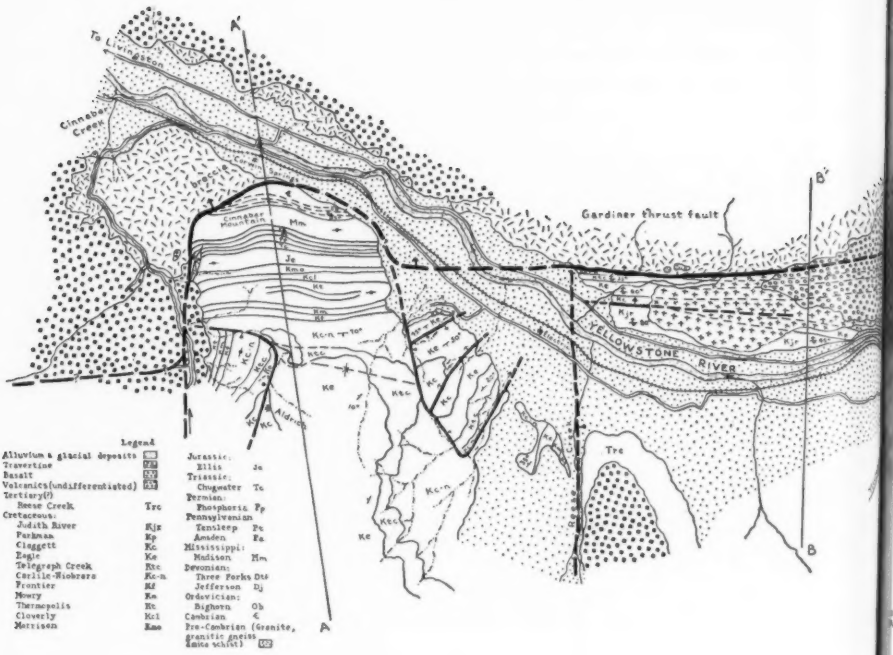


FIG. 2.—Index map of parts of Montana, Wyoming, and Idaho showing the inferred relation of the Gardiner thrust fault to the Beartooth Mountain uplift (ruled area).

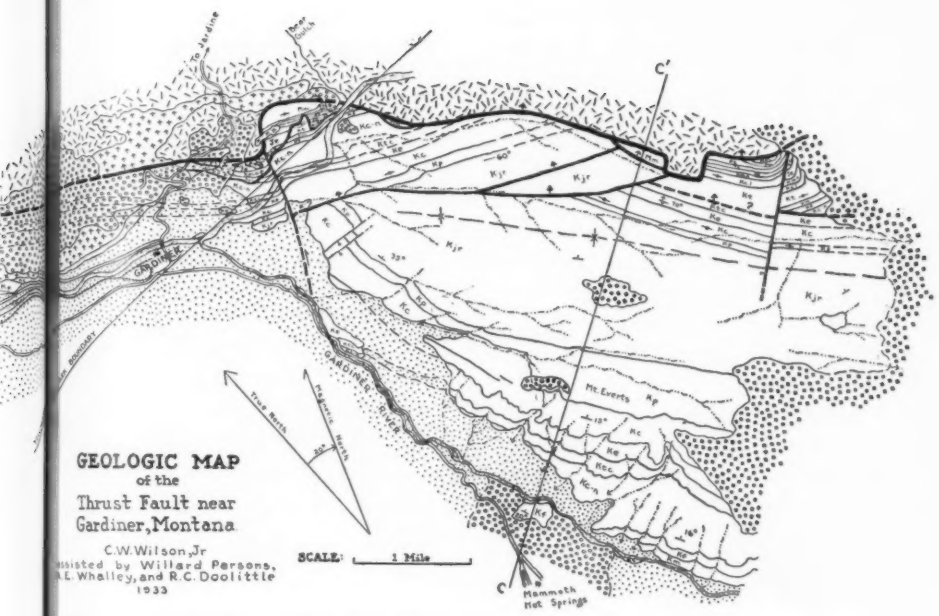
eastern corner of the Three Forks quadrangle, includes the Gardiner thrust fault, and apparently continues through to connect with the basement fault forming the southwest flank of the Rattlesnake Mountain anticline, near Cody. This structural line, the greater part of which is exposed at the surface as a northeastward dipping, high-angle thrust apparently resulted from the underturning and breaking of a southwest-facing monoclinal fold that formed the southwestern margin of the Beartooth uplift (Fig. 2).



Legend

Alluvium & glacial deposits	Qa	Jurassic:	
Travertine	Qt	Ellis	Je
Basalt	Qv	Triassic:	
Volcanics(undifferentiated)	Qv	Chugwater	Tc
Tertiary(?)		Permian:	
Reese Creek	Trc	Phosphoria	Pp
Cretaceous:		Pennsylvanian	
Judith River	Kjr	Tensleep	Pt
Parkman	Kp	Amsden	Pa
Claggett	Kc	Mississippi:	
Eagle	Ke	Madison	Mm
Telegraph Creek	Ktc	Devonian:	
Carlile-Niobrara	Kc-n	Three Forks	Dtf
Frontier	Kf	Jefferson	Dj
Mowry	Km	Ordovician:	
Thermopolis	Kt	Bighorn	Ob
Cloverly	Kcl	Cambrian	€
Morrison	Kmo	Pre-Cambrian (Granite, granitic gneiss Emma schist)	pC

FIG.



— thrust fault, showing direction of dip of fault plane
— normal fault, showing down-dropped wall
— axis of anticline
— axis of syncline
strike and dip of beds
strike of vertical beds
strike and dip of overturned beds

FIG.

Opposing this line of structure and forming the northeastern margin of the Beartooth uplift is the southwestward-dipping, low-angle Beartooth thrust and associated northeast-facing folds of the Beartooth Mountain front. These two opposing lines of thrust and the intervening Beartooth uplift are believed to form a tectonic wedge.

Description of the fault.—The Gardiner thrust fault within the area mapped has a strike of about N. 60° W., and dips approximately 35° to the northeast. In the vicinity of Gardiner (sec. *B-B'*, Fig. 3) the minimum throw is approximately a mile and the minimum heave is approximately a mile and a half.

Apparently the thrusting has been produced by the crowding and partial underthrusting beneath the edge of the rising Beartooth block of the synclinal zone southwest of the major thrust fault—the irregular advance of the underthrusting mass inducing numerous tear faults and subsidiary slicing of the footwall block. Parts of the initial syncline are yet visible near Cinnabar Mountain (Fig. 4) and northeast of Mount Everts.

The trend of the major thrust has been modified by several tear faults. A mile east of Gardiner and close to the Yellowstone River the thrust fault has been offset about 2,000 feet by a tear fault that strikes north-south. The writer postulates a similar tear fault with probably still greater offset on the northwest side of Cinnabar Mountain. Because such a fault would be almost completely covered by Tertiary volcanics it is impossible to determine its presence definitely. The trace of the major thrust fault, however, swings abruptly around the northwestern end of Cinnabar Mountain and follows locally a course at right angles to the main trend of the thrust. Also, the strata on the west side of the mountain have been dragged southwestward as though by a tear fault. Near the center of the western face of this mountain the drag was sufficient to cause minor tear faults (Fig. 4). For these reasons it is believed that such a major tear fault is present at this locality.

Associated thrusting.—One of the noteworthy features of the Gardiner thrust zone is the imbrication and piling-up of thrust slices in the beds just beneath the major plane (Fig. 5). These subsidiary thrust faults, of which eight were mapped within this small area, occur beneath the major fault and dip in the same direction as the

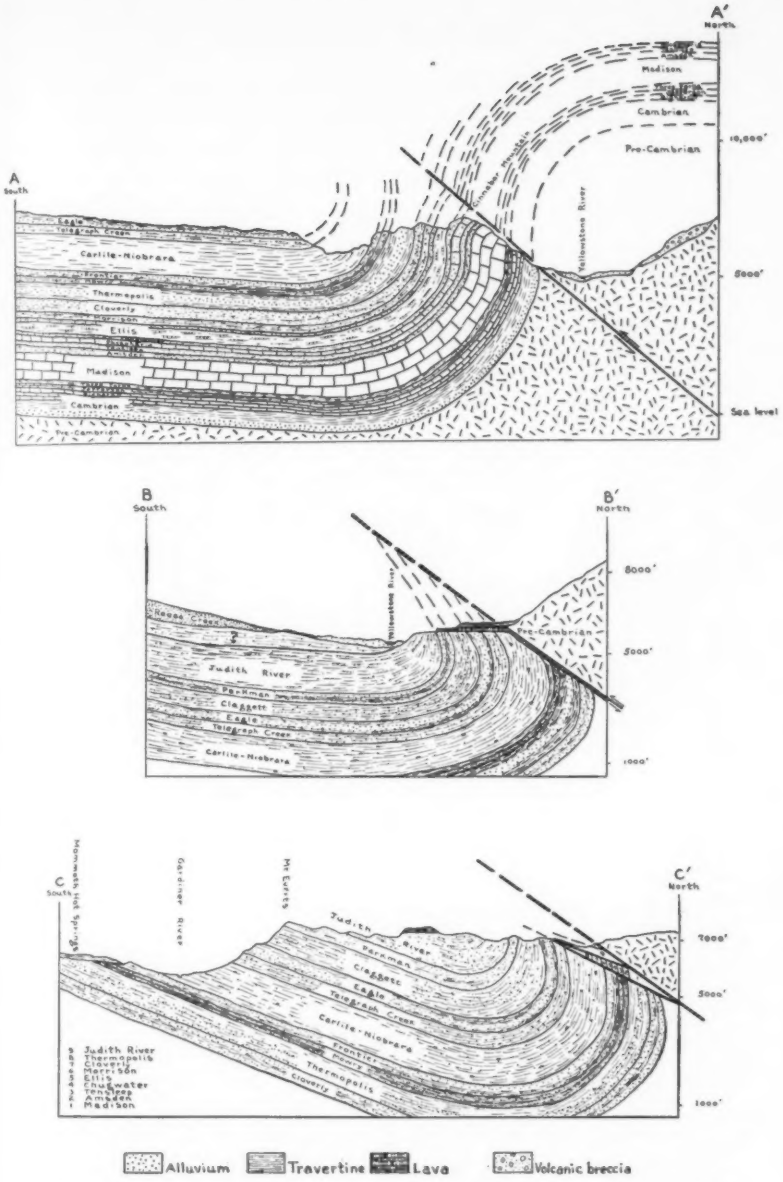


FIG. 4.—Structural cross sections across the map along the lines *A-A'*, *B-B'*, *C-C'*. Scale (horizontal and vertical): 1 inch equals 2,500 feet.

major fault (Sec. *C-C'*, Fig. 3). The planes of some of these subsidiary faults are warped, as is best seen 1½ miles east of Gardiner, between the crossing of the major fault by the Yellowstone River and the tear fault that offsets the major fault. At this locality the irregular trace of the subsidiary fault is not fully explained by the topography.

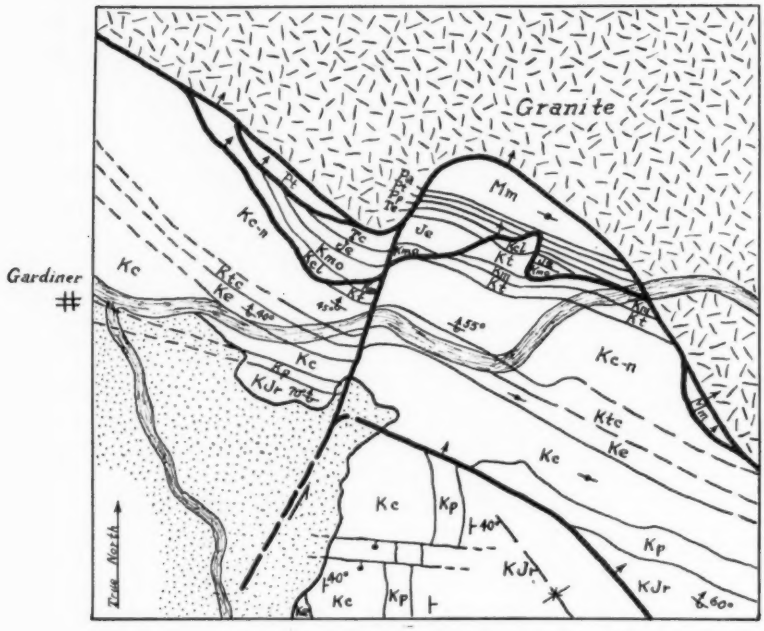


FIG. 5.—An enlarged geologic map of the imbricate faulting about a mile east of Gardiner. Explanation of symbols is given with Fig. 3.

The most accessible locality for seeing the imbricate faulting is about a mile east of Gardiner on the road to Jardine (Figs. 5 and 6). Here erosion has exposed pre-Cambrian upon Tensleep; Tensleep upon Chugwater, Ellis, Morrison, and Cloverly; and these formations upon Carlile-Niobrara, Frontier, and Mowry.

Another striking illustration of subsidiary thrusting is the thrust fault that appears from under the tongue of pre-Cambrian about a

mile west of the point where the major fault disappears under the volcanics at the eastern end of the map (Fig. 4) and extends northwestward more or less parallel to the axis of the syncline. Along this subsidiary fault the vertical and overturned strata of the oversteepened northeast limb of the syncline have been pushed out over the axis of the syncline and the more gently dipping strata of the southwest limb. This causes the syncline to become very sharp, as is well seen in the convergence and meeting of the two belts of outcrop of the Parkman sandstone about $2\frac{1}{2}$ miles northwest of the line of section *C-C'*.

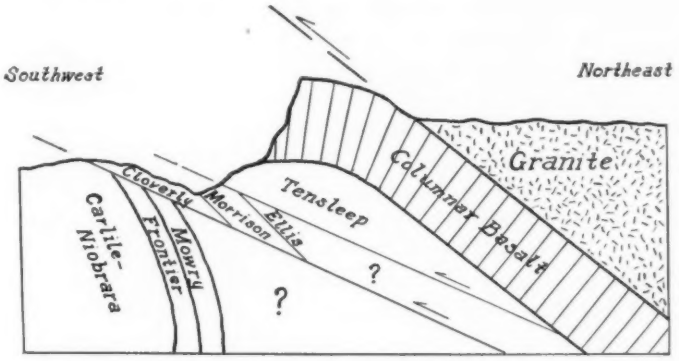


FIG. 6.—Diagrammatic cross section across the fault zone one mile east of Gardiner showing the postulated relation between the basalt and the Gardiner thrust.

Associated normal faulting.—Within the area mapped are several normal faults that developed with the thrusting and so bear significant relations to the tectonic history of the Gardiner thrust. The more important of these will be described.

A fault presumably of normal character and of considerable throw extends along Reese Creek. The Reese Creek formation on the east side of this fault has been dropped to the level of the Thermopolis shale on the west side.

A normal fault of small throw occurs at the eastern end of the map where it offsets beds ranging from the Chugwater to the Judith River. This faulting probably took place at an early stage in the development of the imbricate thrust structure, for it is older than the sub-

sidiary thrust fault that crosses it. The trends of the formations at the northern end of the normal fault and the absence of the Phosphoria formation from between the Tensleep sandstone and the Chugwater formation suggest that the faulting is related to a preexisting anticlinal structure from which the Phosphoria had been removed by erosion or upon which the Phosphoria had never been deposited. The "cracking" of this structure during the development of the imbricate structure would result in such a fault.

The most pronounced normal faults are those bounding the Electric and Aldrich coal fields. These normal faults are closely related in origin to the major downfold and its associated thrust fault.

At some time during the early stages of the development of the fold that was later to be broken by thrusting there was a local "upwarp" in the axis of the syncline at the site of Cinnabar Mountain. This "upwarp" may have been a small cross-structure anticline producing a rise along the axis of the syncline or it may have been a locality along the axis of the syncline that was not downfolded as much as on either side. Regardless of the origin of this feature it formed a positive axis of upwarp normal to the strike of the fold.

This upwarp, present during the folding, shows its effect on the Gardiner thrust by the marked upwarp of the fault plane in order to have extended over the top of the present Cinnabar Mountain. Some of this upward warp in the fault plane may have been postthrust, but the attitude of minor shear faults on both sides of Cinnabar Mountain suggests that the fault plane actually extended over most of the topographic relief present today. The planes of these minor faults are roughly parallel to the slope on both the east and west sides of the mountain. Local rejuvenation would have resulted in the oversteepening of the dip of these faults.

At some time after the fold had begun to develop there were two axes normal to each other, the axis of the syncline along which movement was down and the axis of upwarp along which movement was relatively up. Such a combination of axes produced torsional stresses that resulted in the downdropping of the Electric and Aldrich blocks (Fig. 7).

With further compression of the fold and initiation of thrusting the axis of upwarp became negligible and compression along the axis

of this syncline greatly increased. The thrusting and the increased compression along the axis of the syncline had two effects on the blocks, rotation and intense squeezing of the blocks.

As the continuation of the synclinal axis in the Electric block was more or less parallel to the major thrust fault the resulting strains were chiefly due to compression. This is seen in the intense folding and thrusting that is limited in extent to this block (Fig. 8). The small faults within this block end abruptly where they come in contact with the bounding normal faults.

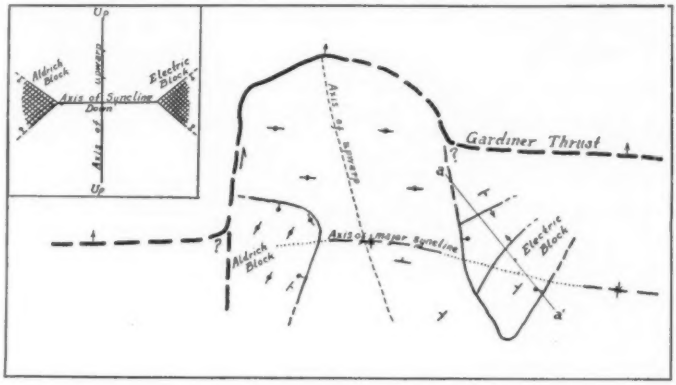


FIG. 7.—Map showing the relation of the Electric block and Aldrich block to the Gardiner thrust fault.

In the Aldrich block the continuation of the synclinal axis was almost perpendicular to the general trend of the major thrust fault. For that reason the deformation of this block is chiefly rotational, the strata having been rotated counterclockwise about 75°. Field evidence of this rotation is well seen in the Eagle and Telegraph Creek formations in the northeastern corner of the block. Here the vertical strata of these formations have been abruptly dragged backward. Evidence of compression is also present in this block, but is not developed to any marked extent as in the Electric block.

Relationship to porphyries.—Along the Gardiner thrust fault, as exposed in the area mapped, and apparently limited to within half a mile of the fault plane, are intrusive bodies of dacite and andesite

porphyry. These are found cutting the granite of the hanging wall. The porphyries may or may not bear a genetic relationship to the thrusting, but because of the distribution of the bodies in a zone within a short distance of the fault plane the writer believes that their intrusion took place along the thrust plane or associated fractures. Inclusions of the dacite porphyry in the andesite porphyry prove that the former is the older of the two.

About a quarter of a mile west of Corwin Springs station is an exposure of breccia (Fig. 4). The matrix of the breccia is probably badly crushed granite, and the fragments are a heterogeneous mixture of

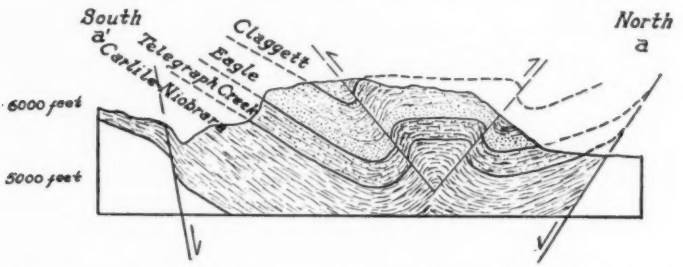


FIG. 8.—Structure cross section across Electric coal field along the line *a-a'* of Fig. 6. Scale (horizontal and vertical): 1 inch equals 1,250 feet.

granite, mica schist, dacite porphyry, andesite porphyry, etc. These fragments are exceedingly angular and some are a foot or so in diameter.

The dating of this breccia was not possible, but it seems logical to assume that it resulted from movement within the fault zone at some time during the period of thrusting.

The distribution of the porphyry intrusives and the occurrence of the breccia within the fault zone suggest the following relations. At some time after the beginning of the thrusting of the underturned syncline, dacite porphyry, and later andesite porphyry, were intruded along fractures within the fault zone and possibly along the major thrust plane itself. Later movement along the major thrust fragmented the porphyries and the granite and incorporated the fragments of both in local breccias.

Relationship to basalt.—At some date after the development of the present topography basalt came up along the plane of the Gardiner thrust. The resulting flows are preserved along the north side of the Yellowstone River for a distance of about 5 miles. The basalts are known to have been extruded from the fault plane because:

1. Their distribution is in an elongate belt along the outcrop of the fault plane.
2. The margins of the flows characteristically end flush along the outcrop of the fault. At some localities the basalt flowed to the southwest, at others northeast, and at one locality a small outlying remnant of basalt extends completely across the fault plane. The direction of flow was wholly dependent upon the direction of slope of the topography with relation to the fault at the time of extrusion.
3. At several localities, notably a mile east of Gardiner on the road to Jardine (Fig. 6), the flows merge with the dikes that fed them. This is shown in the change from vertical columnar jointing in the flows to oblique jointing in the dikes. These dikes occur on the fault plane and have the same strike and dip as the fault plane.

Relationship to travertine.—At a still later date hot springs issued from the fault plane, resulting in the deposits of travertine near Gardiner. These deposits overlie the basalt, and form an elongate belt along the fault plane.

A deposit of travertine also occurs near the junction of Bear Gulch and the Yellowstone River. At this locality the spring which is located upon the outcrop of the fault plane is still actively depositing travertine.

About a mile and a half south of Corwin Springs is a small hot spring by the side of the highway. This spring is within half a mile of the Gardiner fault.

REVIEWS

Fossil Man in China. The Chonkoutien Cave Deposits with a Synopsis of Our Present Knowledge of the Late Cenozoic in China. By DAVIDSON BLACK, TEILHARD DE CHARDIN, C. C. YOUNG, and W. C. PEI. Edited by DAVIDSON BLACK. "Memoirs, Geological Survey of China," Series A, No. 11. Peiping, 1933. Pp. x+1–166; figs. 82, tables 3, maps 6.

A concise and authoritative account of our present knowledge of *Sinanthropus*, of the geologic circumstances of the finds, and of the associated mammalian fauna and lithic industry. The anatomical descriptions are by Black; the remaining sections are principally the work of Teilhard de Chardin. This summary is most welcome because of the scattered nature of the literature on this active and important field of investigation.

The recent death of Dr. Black was a cause of the most profound regret to his fellow-workers in anatomy and paleontology because of the loss at an early age of a brilliant research man, and particularly because he was stricken in the midst of his studies on this very significant material.

A. S. ROMER

Phosphat—Nitrat. By O. STUTZER and W. WETZEL. Berlin: Bornträger, 1932. Pp. xiv+390. Illustrated. Rm 34.

Schwefel—Graphit—Jod—Bor—Magnesit—Talk. By O. STUTZER, W. WETZEL, and A. HIMMELBAUER. Berlin: Bornträger, 1933. Pp. x+396. Illustrated. Rm 32.

O. Stutzer's handbook about non-metallic useful minerals, "*Die wichtigsten Lagerstätten der Nichterze*," appeared in its first edition in two volumes, both written by the author himself. The second edition comprises five volumes by three authors—namely, (1) *Petroleum*, by O. Stutzer, 1931; (2) *Coal*, by O. Stutzer, 1923; (3) *Rock Salt* (in preparation); (4) *Phosphate*, by O. Stutzer; *Nitrate*, by W. Wetzel; (5) *Sulfur and Graphite*, by O. Stutzer; *Iodine and Boron*, by W. Wetzel; *Magnesite and Talcum*, by A. Himmelbauer.

The two volumes with which this review is concerned treat their respective subjects in a much more comprehensive way than was done in

the first edition. The latest literature has been used, and the authors were able to collect much valuable information in the field. O. Stutzer spent two years in Colombia as an oil geologist; and his associate authors are practically, as well as theoretically, acquainted with their subjects. A very large number of new illustrations appear, and bibliographies have been added to several chapters instead of the mere footnotes in the text of the previous edition. The authors have endeavored to pay equal attention to European and overseas deposits.

A. C. Noé

Geology of Eua, Tonga. By J. Edward Hoffmeister. *Petrography.* By Harold L. Alling. *Eocene Foraminifera.* By G. Leslie Whipple. Bernice P. Bishop Museum Bull. 96, 1932. Pp. 93; pls. 22.

This report is based on work with the Tonga Expedition of 1926 under the leadership of Professor W. A. Setchell. The island of Eua is 12 miles long, north and south, and $4\frac{1}{2}$ miles wide, and is surrounded by a narrow fringing reef. Visited by earlier travelers, its geology was described by Lister in 1891, and some of the igneous rocks collected by Lister were described by Harker.

The island has a nucleus of bedded volcanics and a coating of limestone which has been removed in many places. The limestone forms the highest points of the island and is overlain to the west by later volcanics, which are in turn overlain by a late Tertiary limestone. The oldest limestone contains the nautiloid, *Aturia*, lamellibranchs, gastropods, and Foraminifera. Whipple assigns this limestone to the Upper Eocene on the basis of the Foraminifera. It is because he interpreted this Tertiary limestone as a reef that Davis was led to cite this island as the loftiest elevated atoll in the open Pacific.

Well-marked terraces on the eastern side of the island have average altitudes of 100, 200, 340, 400, 550, and 760 feet. The outer edges of the terraces are made up of coral limestone reefs of the late Tertiary. The younger limestones of the terraces are correlated by fossil corals with an elevated barrier reef of the west side. It is therefore maintained that the elevated barrier reef of the west side was formed while the terraces of the east side were being cut, i.e., during intermittent elevation of the island instead of subsidence as proposed by Davis.

The systematic descriptions contain twelve new species of corals and four new species of Foraminifera with a key for the East Indian species of

Pellatispira. From his study of the petrography Alling concludes that Eua is a remnant of a continental series of volcanoes situated on the coast of a former continent.

Professor Hoffmeister's report is an important contribution to the geology of the Pacific and it is gratifying to learn that he and Dr. H. S. Ladd are to continue their careful study of South Sea Islands.

RALPH STEWART

The Geology of Southwestern Uganda, with Special Reference to the Stanniferous Deposits. By H. A. STHEEMAN. The Hague: Martinus Nijhoff, 1932. Pp. xvi & 144. Figs. 187; maps 6. 10 g.

This report, dealing with the region to the west of Lake Victoria Nyanza, is an important addition to the knowledge of the geology of Central Africa. It is abundantly illustrated with photographs, drawings, and maps, and the photomicrographs are particularly clear and well chosen.

The contents are divided into five parts: morphology, regional geology, tectonics, metamorphism, and stanniferous deposits. The first part is concerned chiefly with the processes and results of erosion in a subarid climate. The second section is a discussion of the character and distribution of the rocks of the Karagwe-Ankolian system. Although no positive correlation can be made, the author believes that these rocks, and possibly others which have been named as separate systems in adjoining areas, are equivalent to the Algonkian. Following the deposition of these sediments there was folding accompanied by the intrusion of the granitic magma which was the source of emanations that formed the stanniferous deposits. Although the granite occurs in separate areas, it is believed to be one intrusive mass. The folding of the sediments into transverse synclines separating these areas is explained by longitudinal compression which acted after the system had been folded into a fairly rigid mass by the original forces. The section on tectonics closes with the presentation of inconclusive evidence that the granite was injected along the base on which the Karagwe-Ankolian system was deposited.

In the chapters on metamorphism, detailed descriptions are given of both autometamorphism and allometamorphism. This subject is closely related to that of the genesis of the pegmatitic tin veins, which the author considers to be chiefly of metasomatic origin. In the section which describes these deposits particular attention is given to the sequence of replacement in the formation of the veins and to the factors which controlled their distribution.

EDWARD L. TULLIS

Clay and Shale Resources in Southwestern Pennsylvania. By HENRY LEIGHTON with laboratory tests by J. B. SHAW. Harrisburg, Pa. Topographic and Geologic Survey of Pennsylvania, Bull. M 17, 1932. Pp. 190; figs. 16; tables 27.

In southwestern Pennsylvania, a region well known for its beds of coal, occur valuable deposits of clay and shale which often are associated closely with the coal. Beds of commercial clay and shale occur at a number of horizons throughout the section, but the best deposits are of Pennsylvanian age. Clays deposited during the Glacial period are found locally. In the area of ten counties included in this report the underlying formations range in age from Upper Devonian to Lower Permian.

The opening pages give brief discussions of physiography and stratigraphy, more complete descriptions of the properties of the clays and shales, and unusually good summaries of the physical, burning, and chemical tests of clay, and of the requirements for various types of products. The principal part of the report is devoted to descriptions of the deposits by counties. Here are included both generalized and detailed geologic sections, and full accounts of the distribution, development, geologic relations, ceramic properties, and possible uses of the various clay and shale beds. The tables, showing chemical analyses, physical tests, and suggested utilization, give much valuable information and represent a great amount of work.

EDWARD L. TULLIS

The Geology of the Cheviot Hills (based on the work of C. T. Clough and W. Gunn). By R. G. CARRUTHERS, G. A. BURNETT, and W. ANDERSON, with petrological notes by H. H. THOMAS. Memoirs of the Geological Survey of England and Wales, Explanation of Sheets 3 and 5. London: His Majesty's Stationery Office, 1932. Pp. xi+174; figs. 2; pls. 7. 4*s.* 0*d.*, plus postage.

This memoir replaces two smaller ones issued about forty years ago. The portion of the Cheviot Hills described lies in Northern England adjacent to the Scottish border. The chief formations of the area are intrusives and flow rocks of Old Red Sandstone age overlain by sediments of the Lower Carboniferous and by glacial deposits.

Three pages of the Introduction, devoted to a summary of the geological history and formations, are of most interest to one who is not concerned with the detailed descriptions that occupy the largest part of the volume. In describing the petrology of the lavas and of the granites

which intrude them attention is given to contact alterations in the lava and to changes in the granite caused by absorption of the more basic rock. An interesting account of the drainage changes during the last glaciation is given. Included in the Appendix are a number of detailed sections through the coal beds.

EDWARD L. TULLIS

On the Earth-Vortex, Echelon Faults and Allied Phenomena. By S. FUJIWHARA, T. TSUJIMURA, and S. KUSAMITSU. Sonderdruck aus Ergebnisse der Kosmischen Physik, Band II. Leipzig: Akademische Verlagsgesellschaft M. B. H., 1934. Pp. 570; figs. 50.

Although this paper is, to a considerable extent, a restatement of the senior author's previous work, structural geologists, especially those unfamiliar with S. Fujiwhara's earlier papers, will find a number of interesting ideas presented. Readers will find the English somewhat cumbersome, the illustrations good, and the Bibliography excellent.

Differences between the surveys of 1884–99 and 1924–25 indicate a vortex movement of the earthcrust around Sagami Bay, Japan. The method of calculating principal stresses, divergence, shear, and rotational movements is shown; and the close relation of the principal stress points of the vortex to the principal orogenic movements in the region is pointed out. The writers suggest and illustrate the application of the principle of vortex motion to the structural complexities of Scotland, the Alps, the Himalayas, and circum-Pacific areas. These portions of the paper carry a slight Wegenerian flavor.

The writers discuss the value of model experiments and hold that they must be used with utmost caution, but several laws formulated to explain vortical movements, crack, and echelon arrangements are based mainly on model experiments.

GORDON RITTENHOUSE

The Gondwana System and Related Formations. By CYRIL S. FOX. *Memoirs of the Geological Survey of India,* Vol. LVIII. Pp. 241; pls. 10.

This *Memoir,* in treating certain phases of the stratigraphy of India, touches upon three problems of wide geologic significance: (1) pre-Permian age of the Talchir glacial beds; (2) the unity of the Gondwana system; and (3) the former existence of a "Gondwanaland."

1. The late Carboniferous rather than early Permian age of the Talchir boulder beds has been established to the satisfaction of most students. The findings presented in this *Memoir* emphasize that conclusion.

2. The Geological Survey of India for more than fifty years has considered the Gondwana system to be comprised mostly of terrestrial strata beginning with the Talchir and including all rocks up to the Umia beds which some regard as late Jurassic and others as Neocomian in age. Reasons for the unity of this classification are convincingly presented in the *Memoir*.

As the classification of these strata stands in the *Memoir*, the Gondwana system straddles two eras. By simply classing the Talchir beds and immediately overlying strata as Mesozoic, this overlapping could have been avoided. The principle of ultimate correlation by diastrophism finds a perfect example in the Hercynian revolution followed by glaciation. The observations of the Indian Survey indicate a closer affinity of the Permian to the Mesozoic than to the Paleozoic. The only marine fauna found in this debatable section of the column is markedly transitional. It also seems possible that revaluation of the Permian of the Northern Hemisphere may further emphasize the importance of the Hercynian revolution in marking the transition between the Paleozoic and the Mesozoic.

3. Dr. Fox cites "proofs" of the former existence of a "Gondwanaland" which later split, according to the "continental drift theory," into several continents. The rapid distribution of the *Glossopteris* flora over the southern continents during early Gondwana time, is presented as one of these proofs. But it is well known that recently arisen South Sea islands have well-developed floras, although a thousand miles of open water separates them from the nearest continental land. Some other explanation than that of "drifting continents" to account for rapid distribution of plant species is easily found.

According to the *Memoir*, the "breakup of Gondwanaland" occurred at the close of the Cretaceous. Yet paleobotanical evidence shows that there was about as free migration of plants until the middle of the Tertiary as there had been during Gondwana time.

RANDALL WRIGHT

The Geology of Malaya. By J. B. SCRIVENOR. London: Macmillan Co., 1931. Pp. 216; illus. 45; colored map. 16*s*.

This is intended as a companion volume for *The Geology of Malayan Ore Deposits* by the same author and takes up the geologic history of the

peninsula, with brief reference to the economic features. The structure and stratigraphy are well set forth and bring to our attention a number of new facts. The Malay Peninsula is not traversed by one central ridge beginning in Siam, but by a series of *en échelon* folds which are related to those of Siam and Burma. Paleontology and faunal migrations are discussed in the account of the sedimentary rocks and a notable amount of space is devoted to stratigraphy, which the author feels needs unification because of the large amount of unrelated work which has been done.

All of the rocks and minerals which have been found in Malaya are catalogued, whether they are of economic value or not, and one chapter is devoted to rock weathering—particularly to the development of laterite. A complete bibliography concludes the volume.

J. T. McC.

Natural Gas in Western Kentucky. By WILLARD ROUSE JILLSON. Kentucky Geological Survey (6th ser.), Vol. XXXVIII. Frankfort, Ky., 1931. Pp. 190; maps 23.

Oil and Gas in Western Kentucky. By WILLARD ROUSE JILLSON. Kentucky Geological Survey (6th ser.), Vol. XXXIX. Frankfort, Ky., 1930. Pp. 632; maps 45.

Oil and Gas in the Bluegrass Region of Kentucky. By WILLARD ROUSE JILLSON. Kentucky Geological Survey (6th ser.), Vol. XL. Frankfort, Ky., 1931. Pp. 123; maps 45.

In the first of these reports the author discusses some nineteen gas fields in the area west of Louisville and east of Evansville, Indiana. The second report summarizes the stratigraphy and geological structure of western Kentucky. In the third report the author sets forth his reasons for believing that the possibilities of encountering gas in the central-northern Bluegrass region and in the far-western portion of Kentucky are better than previous geological work in this area would indicate. The report is not so encouraging with respect to oil.

All three volumes are complete with well logs, short summaries of stratigraphy and geological structures, and brief histories of previous drilling in the areas treated.

H. W. STRALEY III

Geology der Insel Ischia. By A. RITTMANN. Berlin: Dietrich Reimer (Ernst Vohsen), 1930. Pp. 265; pls. 12; figs. 55; maps 2. M. 38.

Rittmann has given us a very thorough and interesting account of the geology of this little volcanic island which lies off the west coast of Italy, about 18 miles southwest from Naples. The physiography, structure, and volcanic nature of the island are almost inseparable and are treated together. Much space is devoted to descriptions of igneous rocks—some of the analyses are by H. S. Washington—and to hot springs, fumeroles, and active vents. Sedimentary rocks also occur; some are fossiliferous and a long fossil list will attract the attention of paleontologists.

This book is well written, in an easy and interesting style. The maps and illustrations are of the very best. Anyone interested in a detailed study of Italian volcanic islands will do well to read what Rittmann has to say.

J. T. McC.

The Natural History of Indian Coal. By CYRIL S. FOX. "Memoirs of the Geological Survey of India," Vol. LVII. Pp. 283; pls. 17.

This volume discusses the origin and formation of coal especially from the viewpoint of the Indian occurrences. The author believes that coal was formed rapidly from transported material laid down in comparatively deep, non-stagnant water.

The book includes an excellent discussion of the terminology of coal constituents. While some readers will incline toward alternative interpretations of evidence cited by Dr. Fox in support of theories given in this work, nevertheless the wealth of references and of physical and chemical data contained entitle the book to a prominent place in coal literature.

RANDALL WRIGHT

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